

Damage Evaluation & Analysis of Composite Pressure Vessels Using Fiber Bragg Gratings to Determine Structural Health



Marley Kunzler^a, Eric Udd, Stephen Kreger
Blue Road Research
Gresham, Oregon 97030

Mont Johnson & Vaughn Henrie
ATK Thiokol
Brigham City, Utah 84302

^a Author correspondence: marley@bluerr.com

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE FEB 2005		2. REPORT TYPE		3. DATES COVERED -	
4. TITLE AND SUBTITLE Damage Evaluation and Analysis of Composite Pressure Vessels Using Fiber Bragg Gratings to Determine Structural Health			5a. CONTRACT NUMBER F04611-02-C-0007		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Marley Kunzler; Eric Udd; Stephen Kreger; Mont Johnson; Vaughn Henrie			5d. PROJECT NUMBER 3005		
			5e. TASK NUMBER 02AG		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Blue Road Research,Gresham,OR,93524-7680			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT N/A					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 60	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

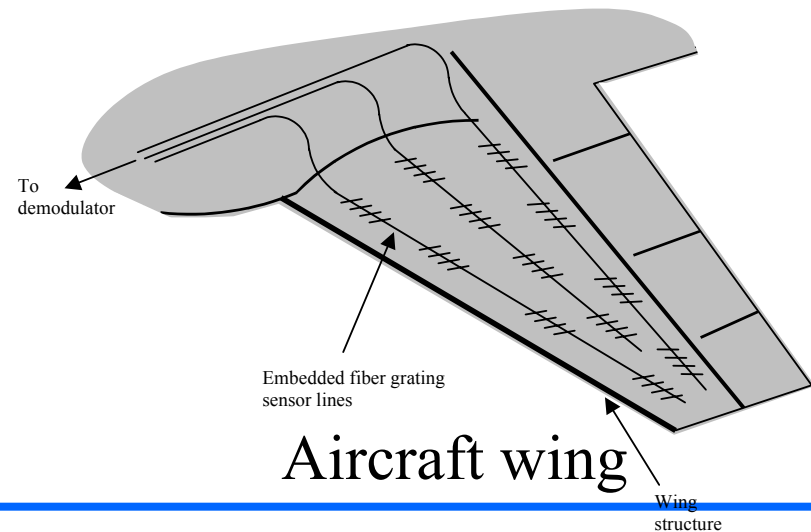
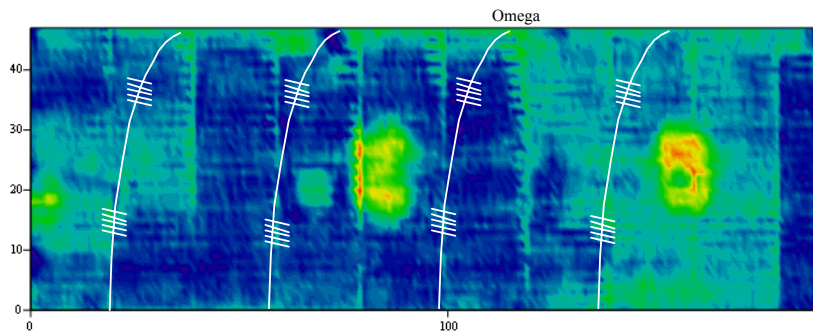
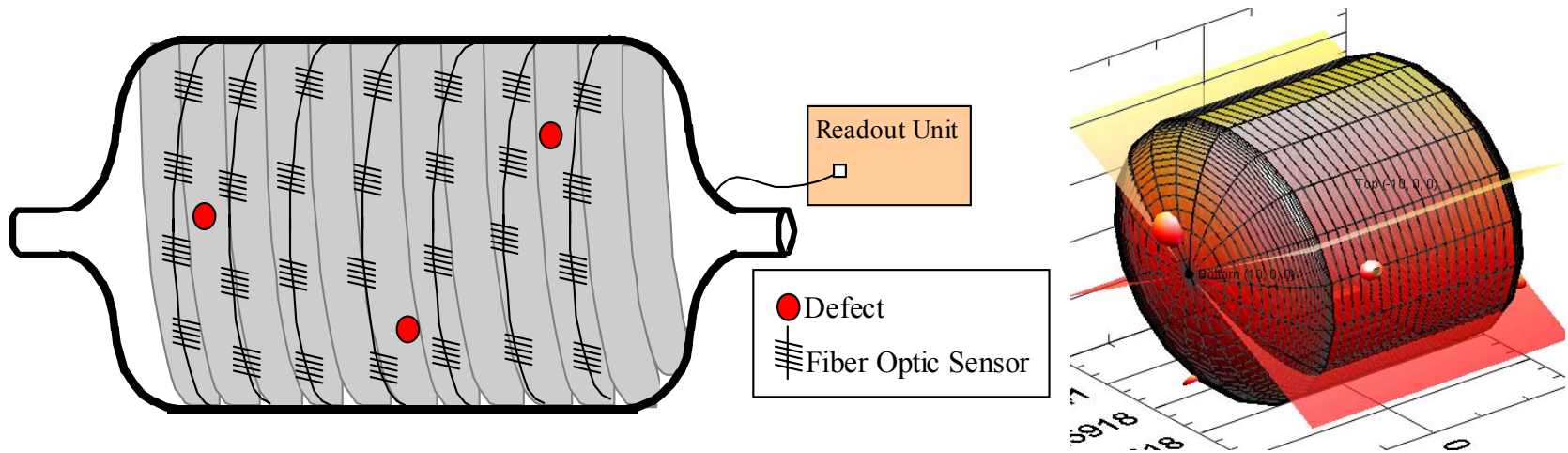
Acknowledgements

Blue Road Research would like to acknowledge funding support for this research effort from the SBIR Phase II Air Force Contract F04611-02-C-0007. Additional support was provided under the SBIR Phase II Air Force Contract F33615-02-C-5043

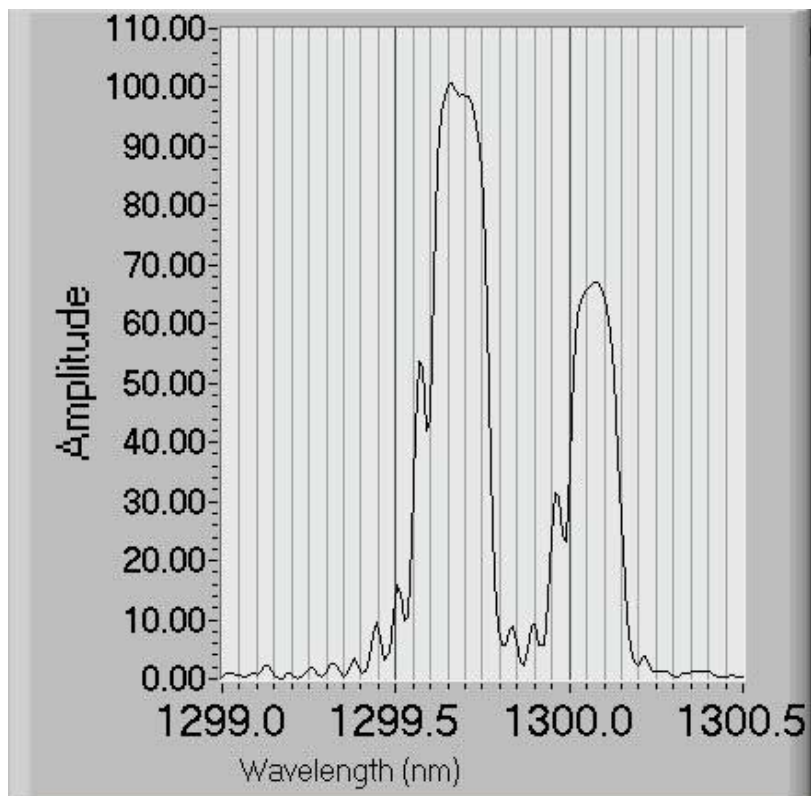
Overview

- Why Composites & Fiber Optics?
- Readout System Overview
- Experiments:
 1. Impact Quantification
 2. Manufacture/Cure
 3. Blind Impacts
 4. Dynamic ‘Strain Imaging’
- Conclusions & Future Work

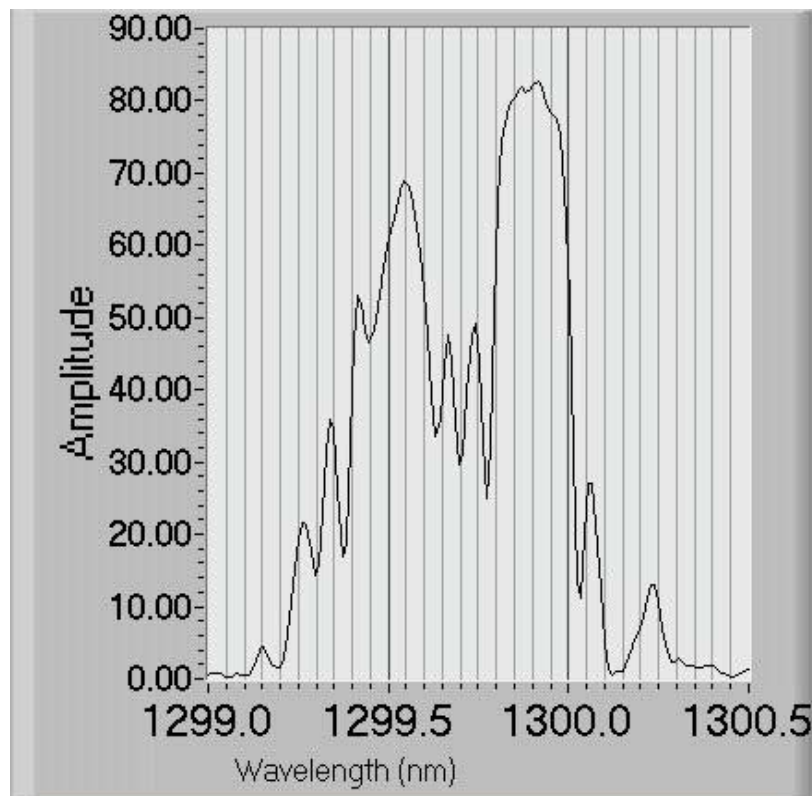
Composite 'Smart Systems'



Multi-Axis Information



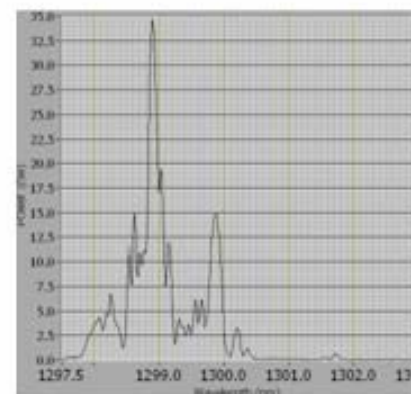
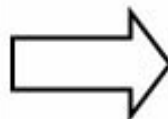
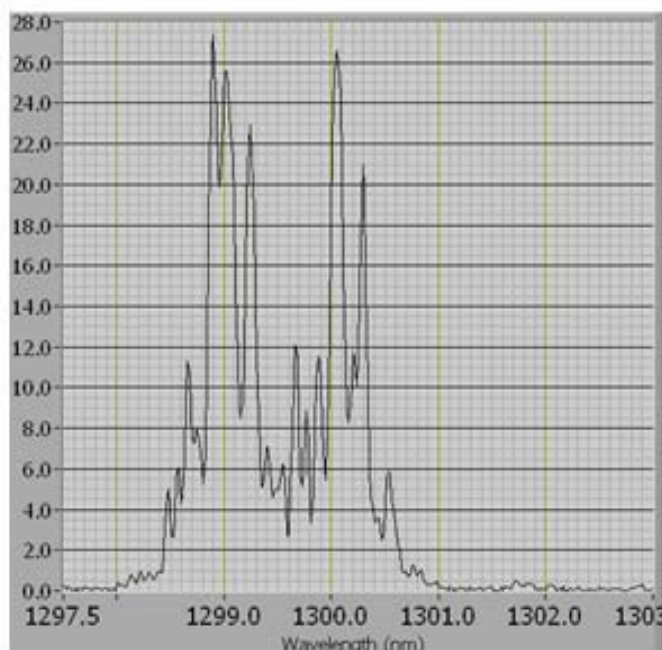
(a)
before



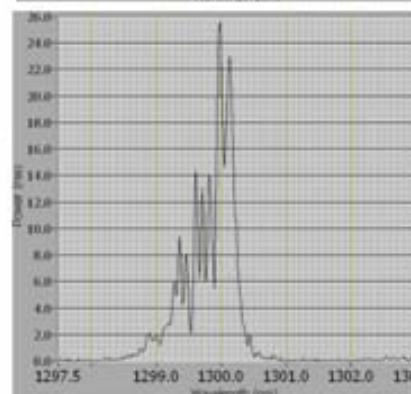
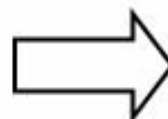
(b)
after

Multi-Axis Separation of Data

Dual-Axis Grating Under “Strain”

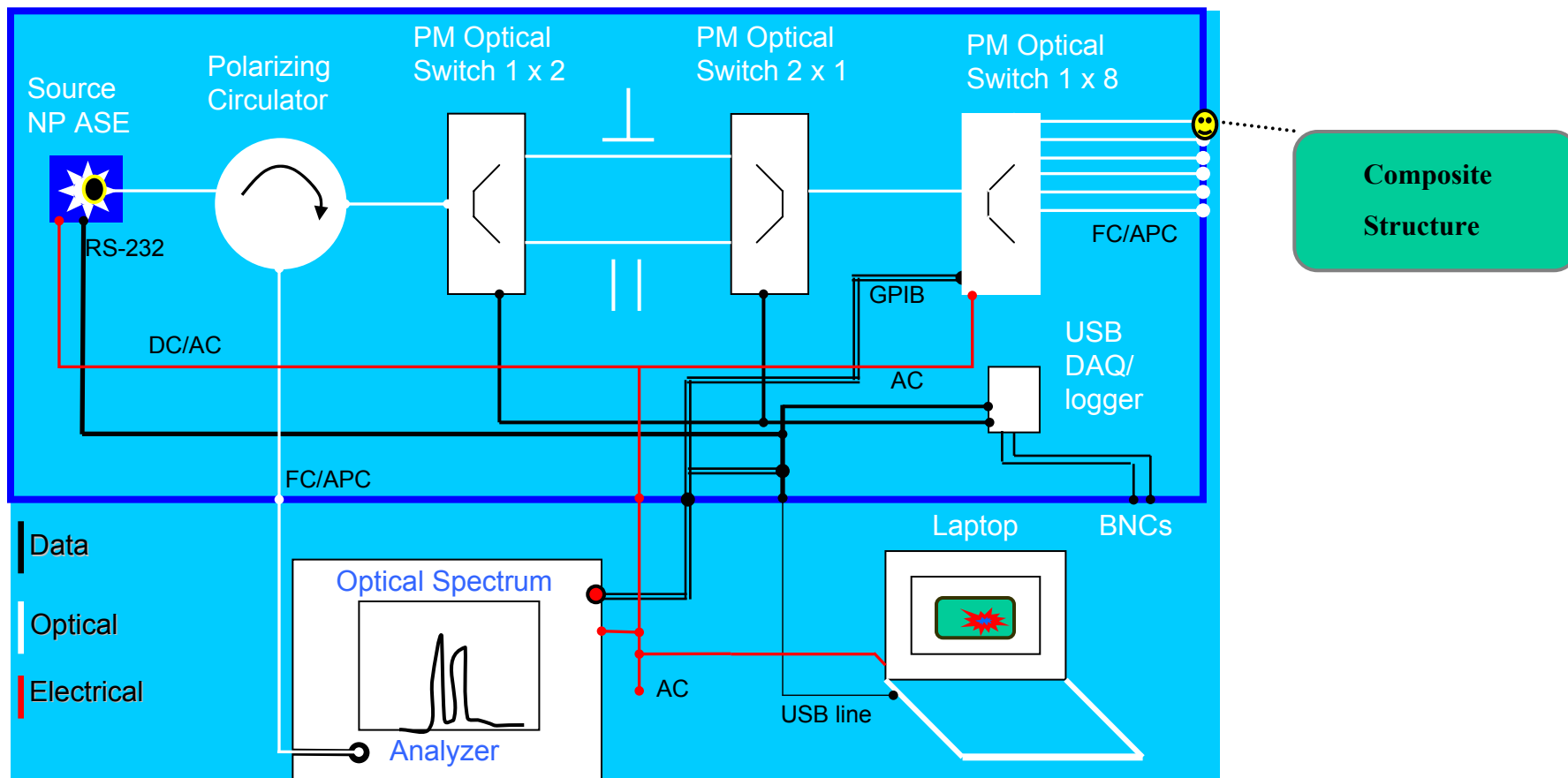


In-Plane
Component

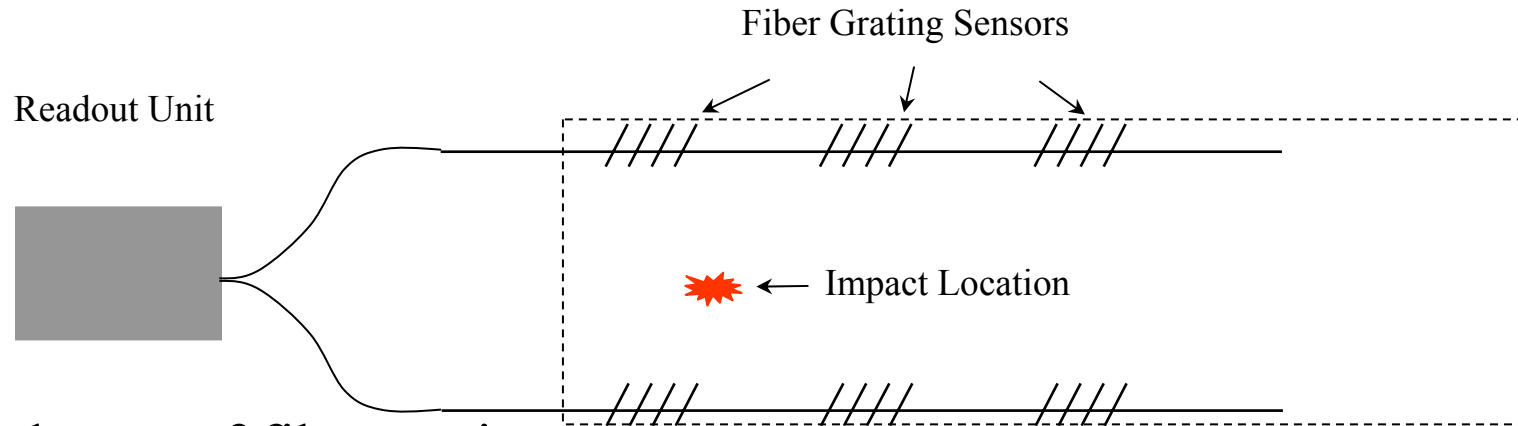


Out-of-Plane
Component

Composite Health Monitoring System



Composite 'Strain Image'

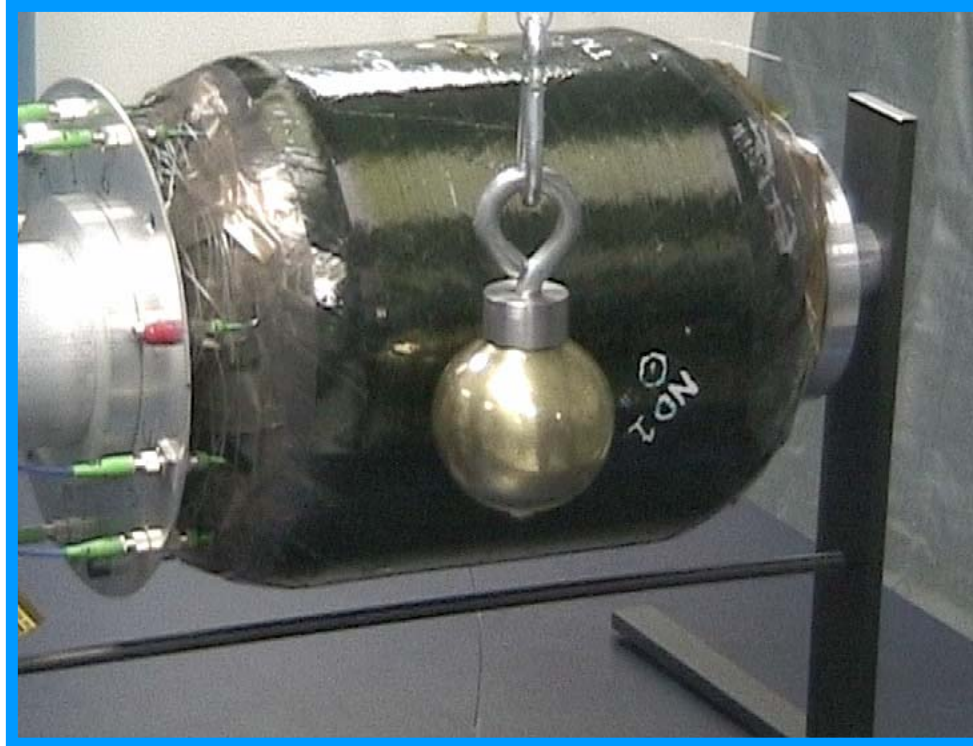


Embedment of fiber optics
for damage/health
evaluation

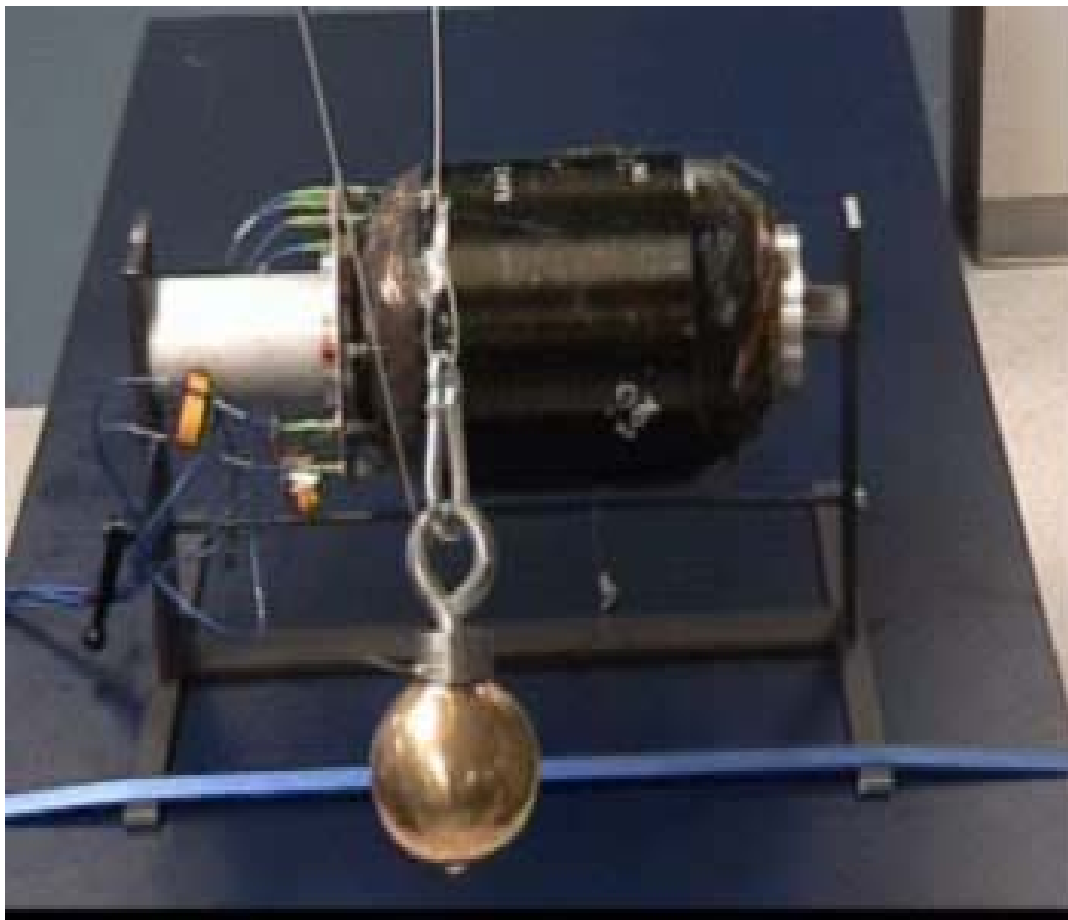
Composite Strain Image:



Experiment 1: Impact Quantification



5 ft-lbs Impact



10 ft-lbs Impact



15 ft-lbs Impact



Damage Output Before Impact



Damage Output After 5 ft-lb Impact



Damage Output After 10 ft-lb Impact



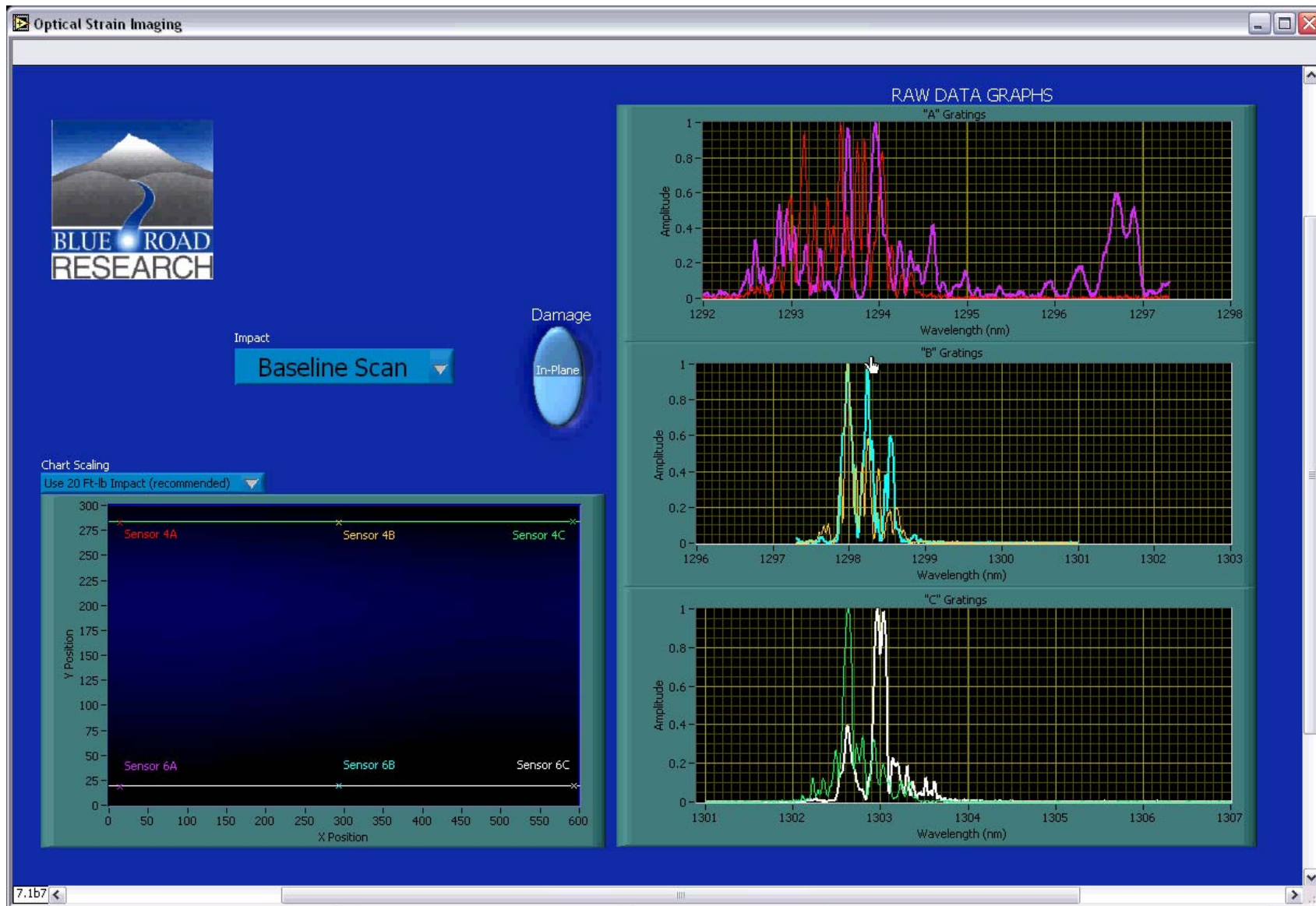
Damage Output After 15 ft-lb Impact



Damage Output After 20 ft-lb Impact

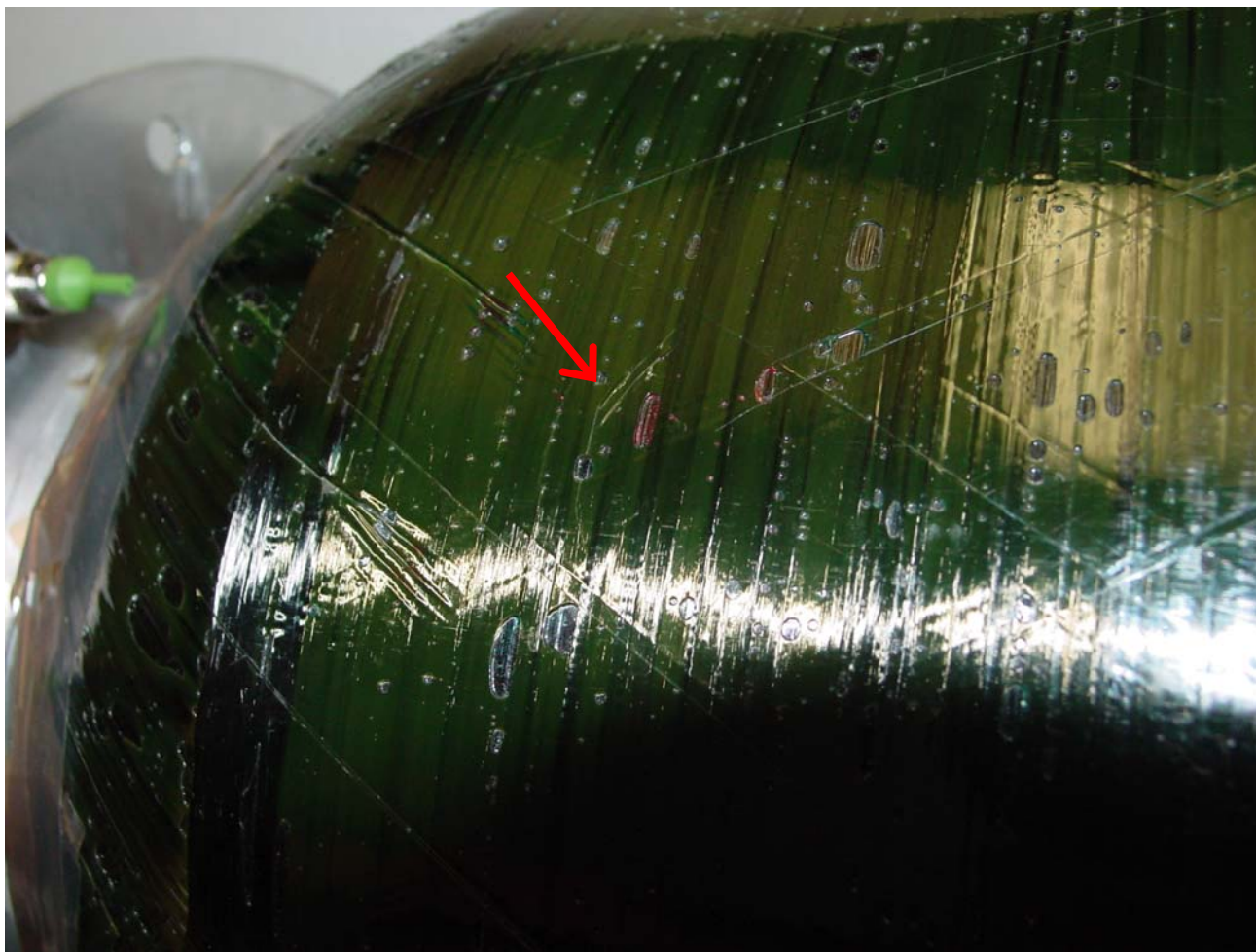


Strain Imaging Demonstration



Strain Imaging Bottle Impact Test

Damage Area After All Impacts

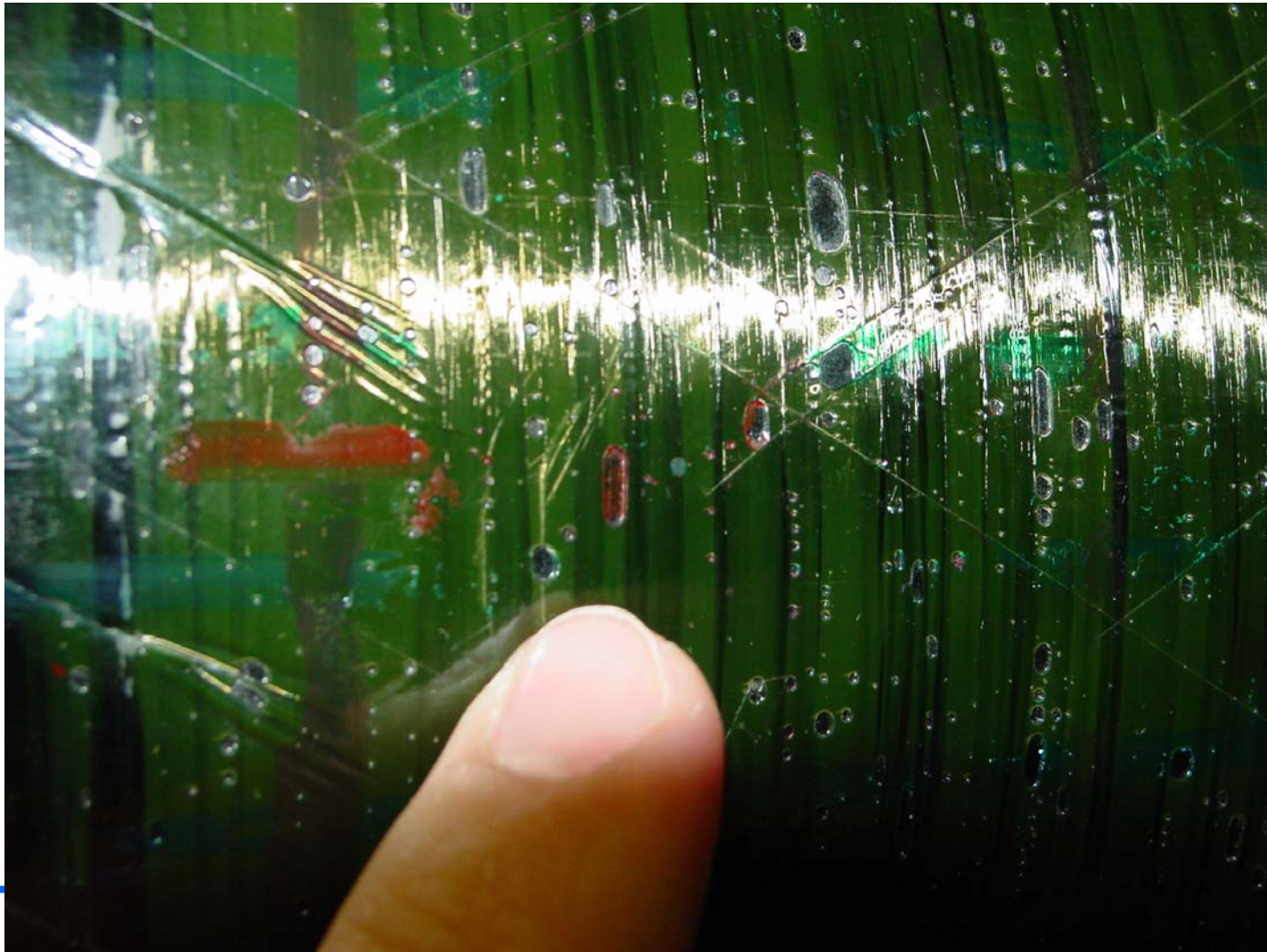


Strain Imaging Bottle Impact Test

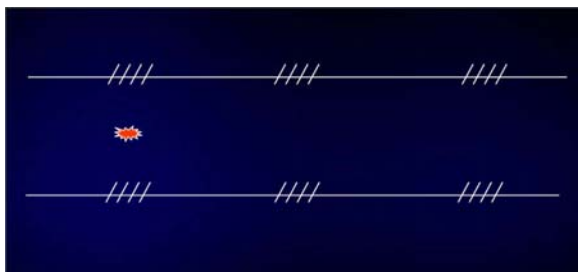
Damage Area After All Impacts



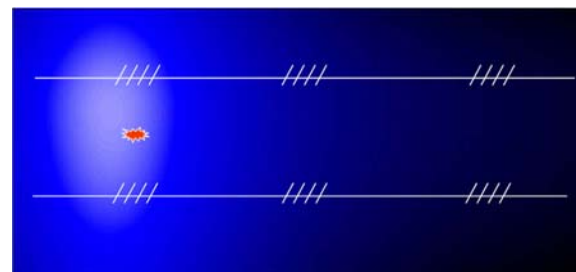
20 ft-lbs Impact



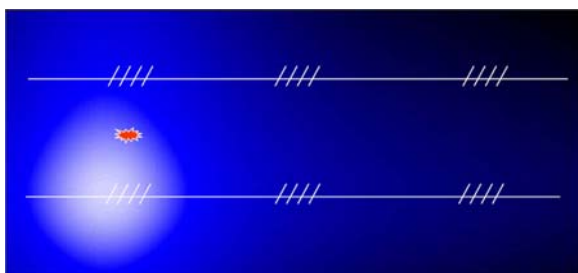
Reduction of Data:



Before Impact



After 1st Impact

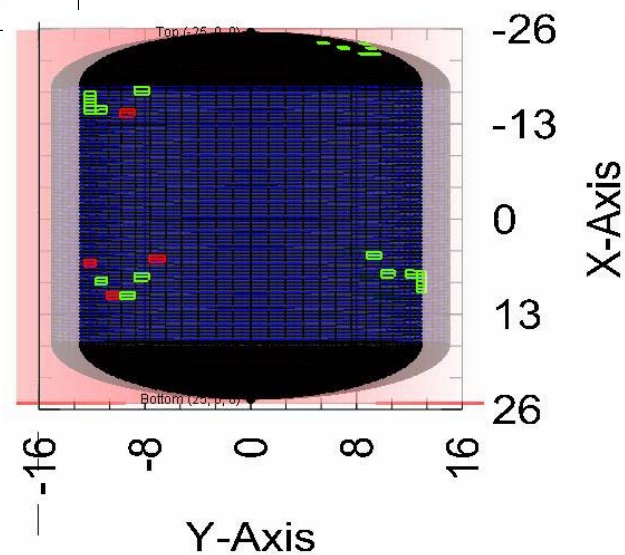
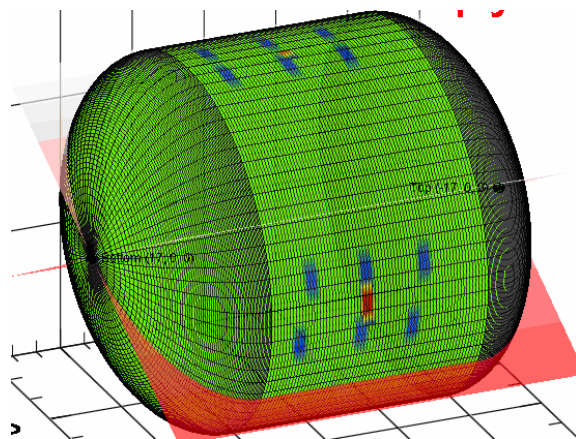
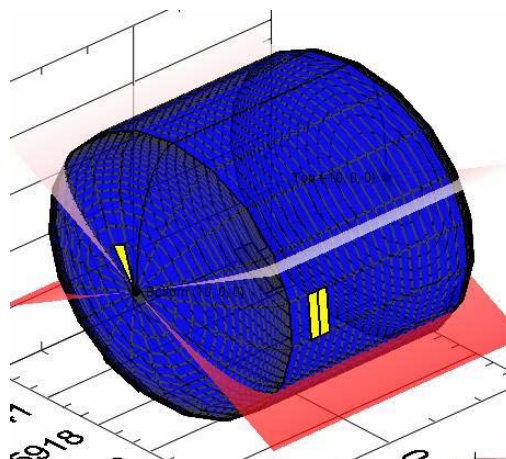
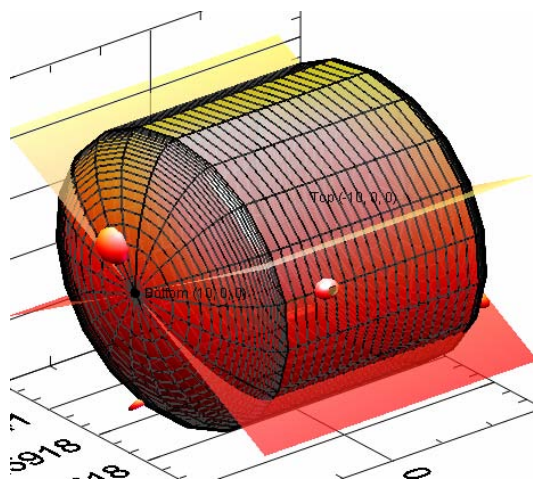


After 2nd Impact

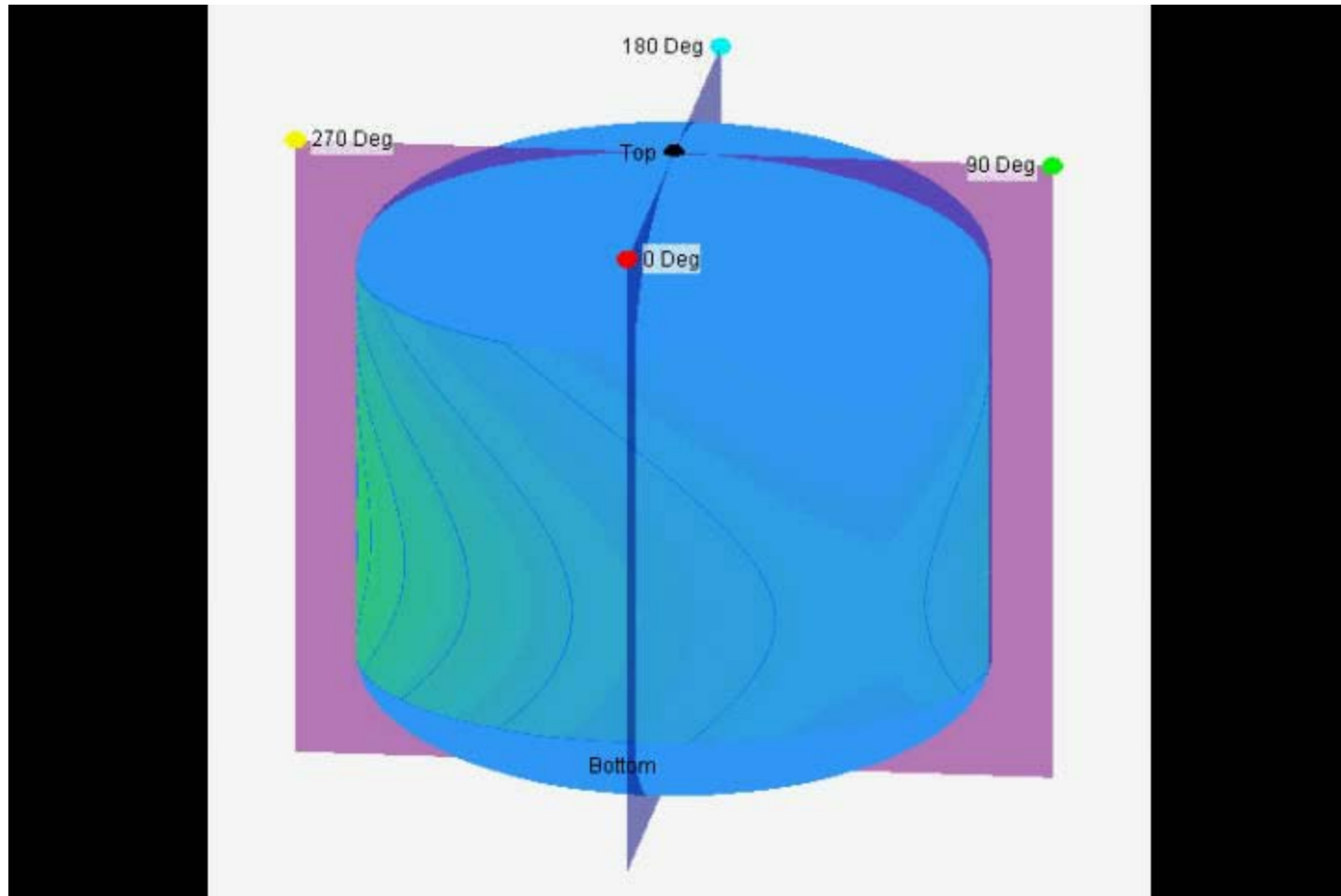


After 3rd Impact

Simplified Ideas to Show Damage

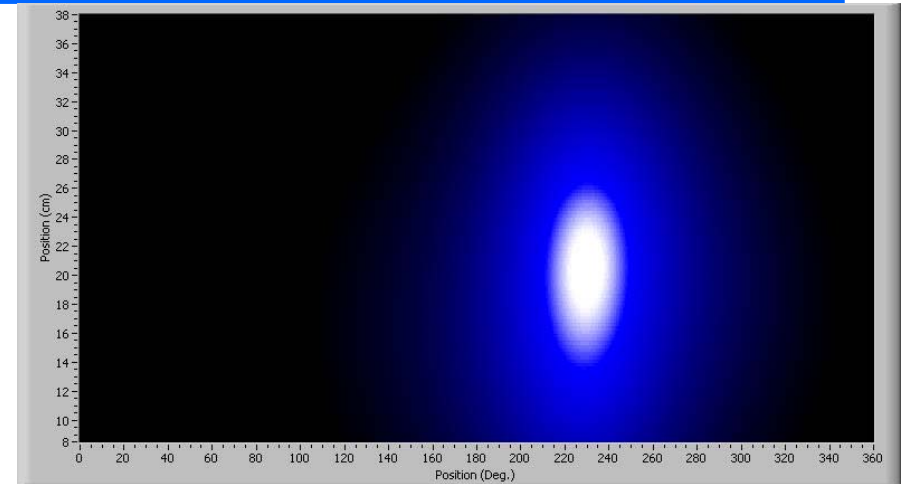
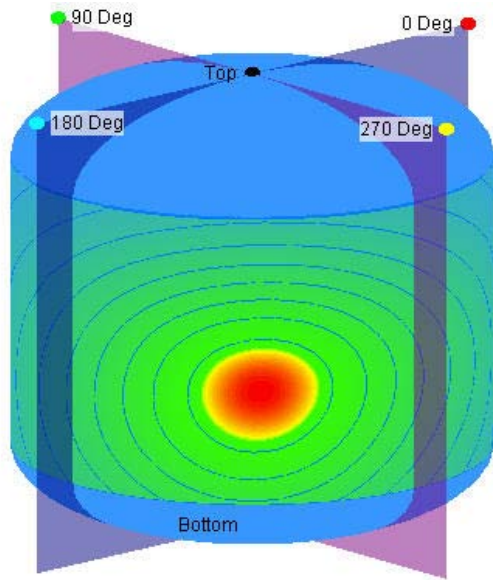


Simplified Display



Actual Data, Motor Casing #3, Impact #3

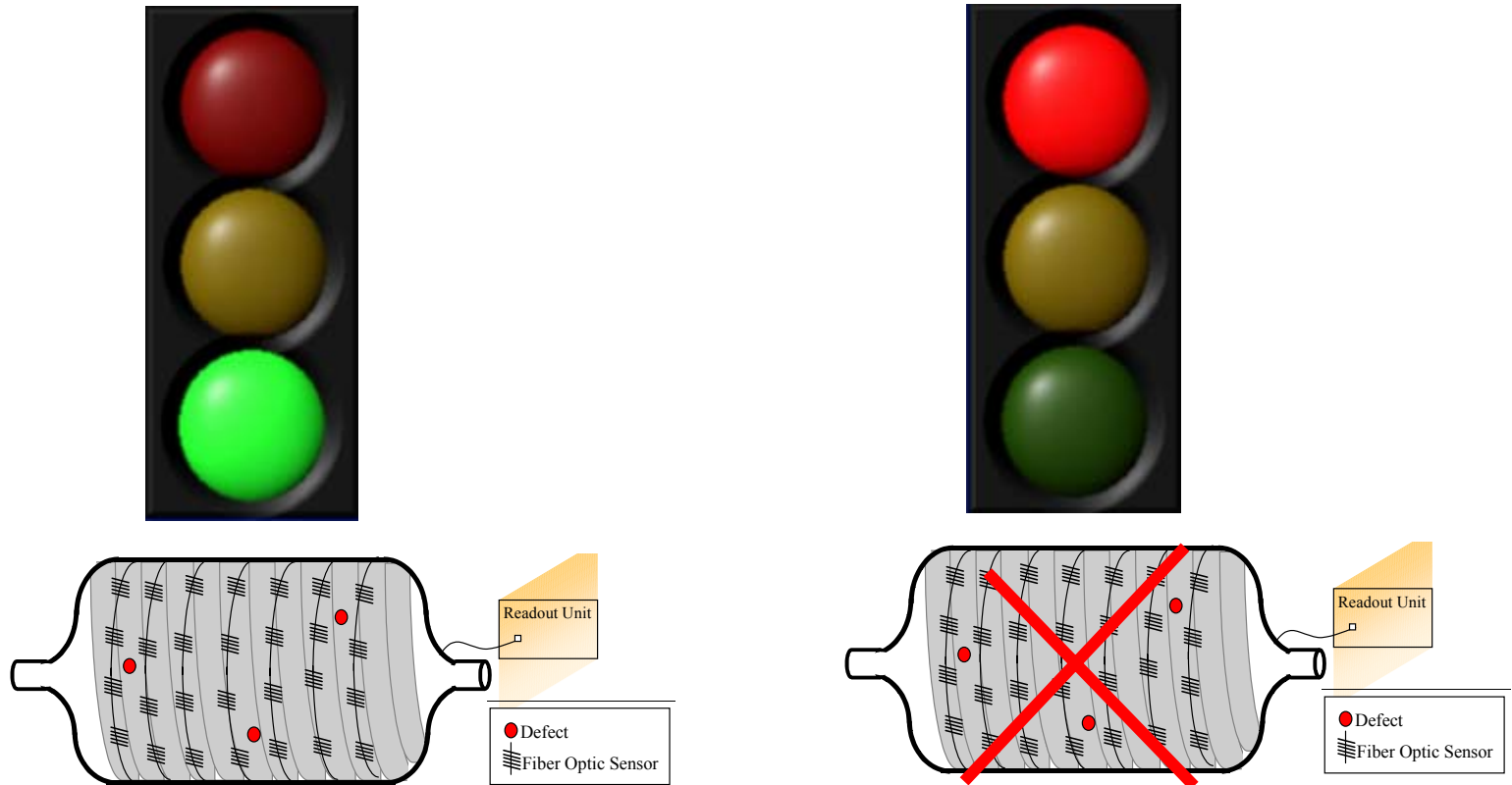
Simplified Display



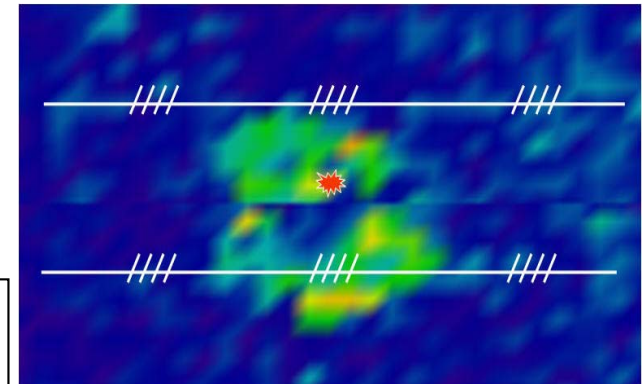
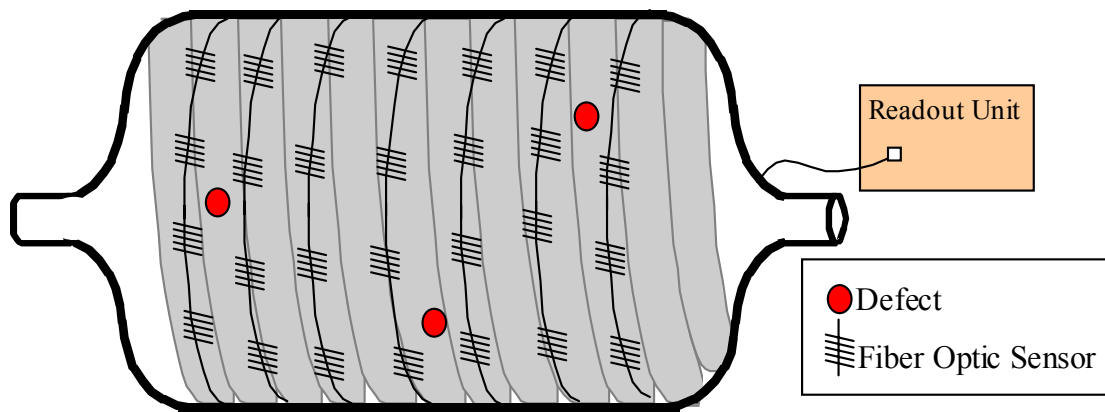
Force: 24.3 ft-lbs
15.0 cm Distance from Flange
47 cm Distance from 0 Degrees

Degree Measurement: 222.6 °

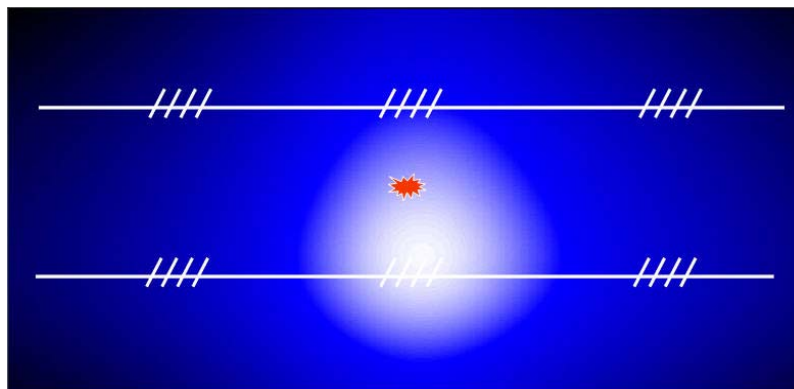
Goal – ‘Digital’ Analysis



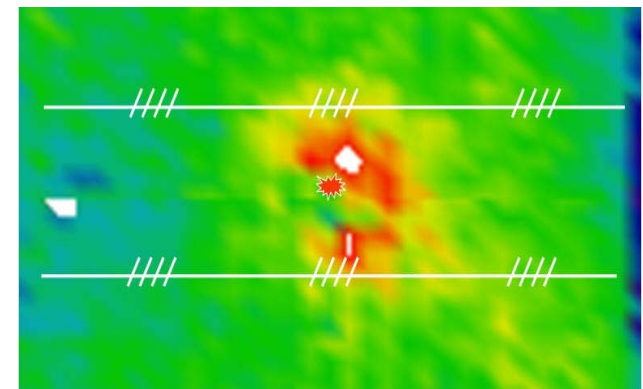
Strain Imaging, Ultrasonic and Eddy Current Scans-Impact Damage in a Composite



Ultrasound



FBG Strain Imaging



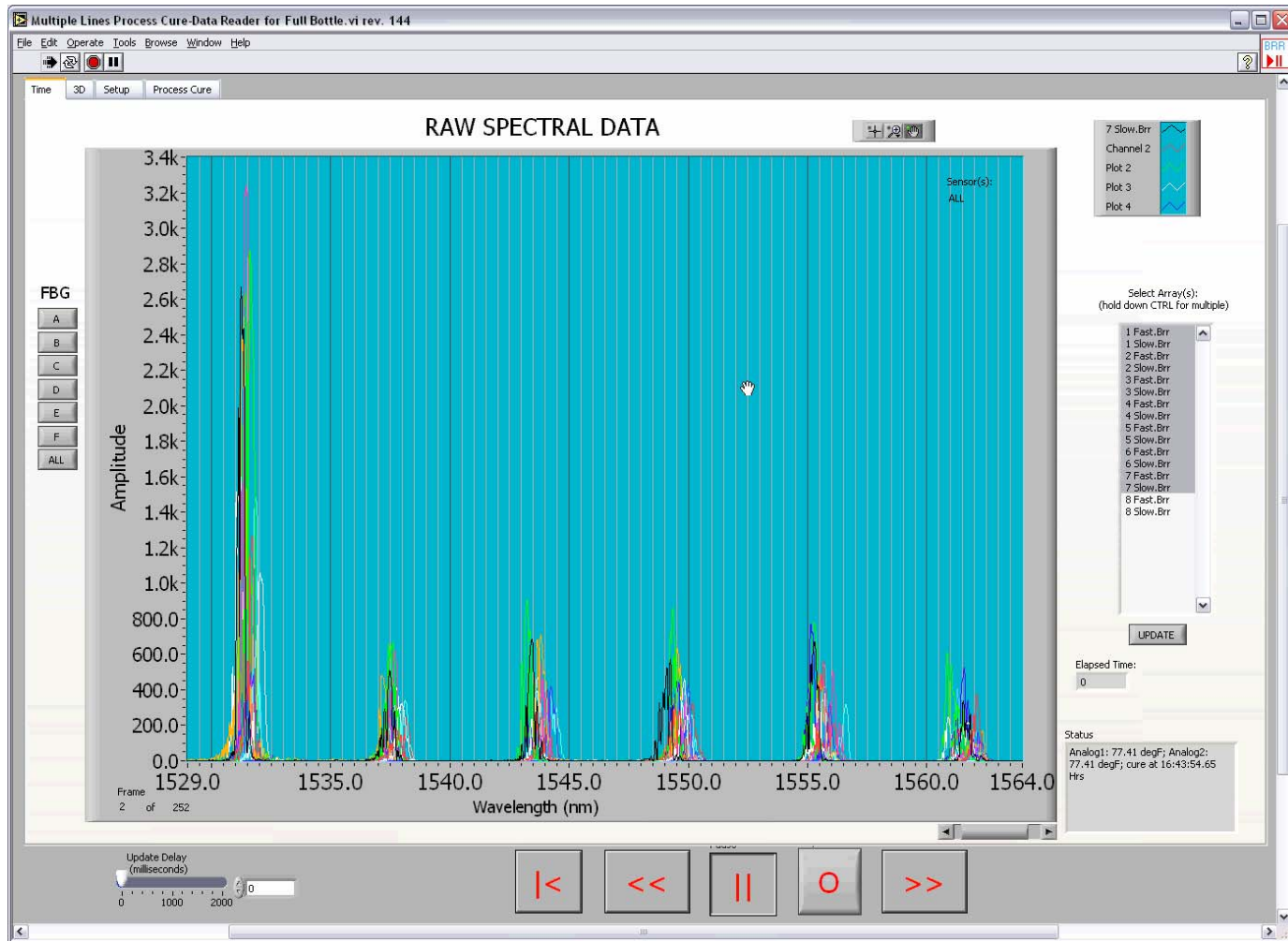
Eddy Current

Recent Progress

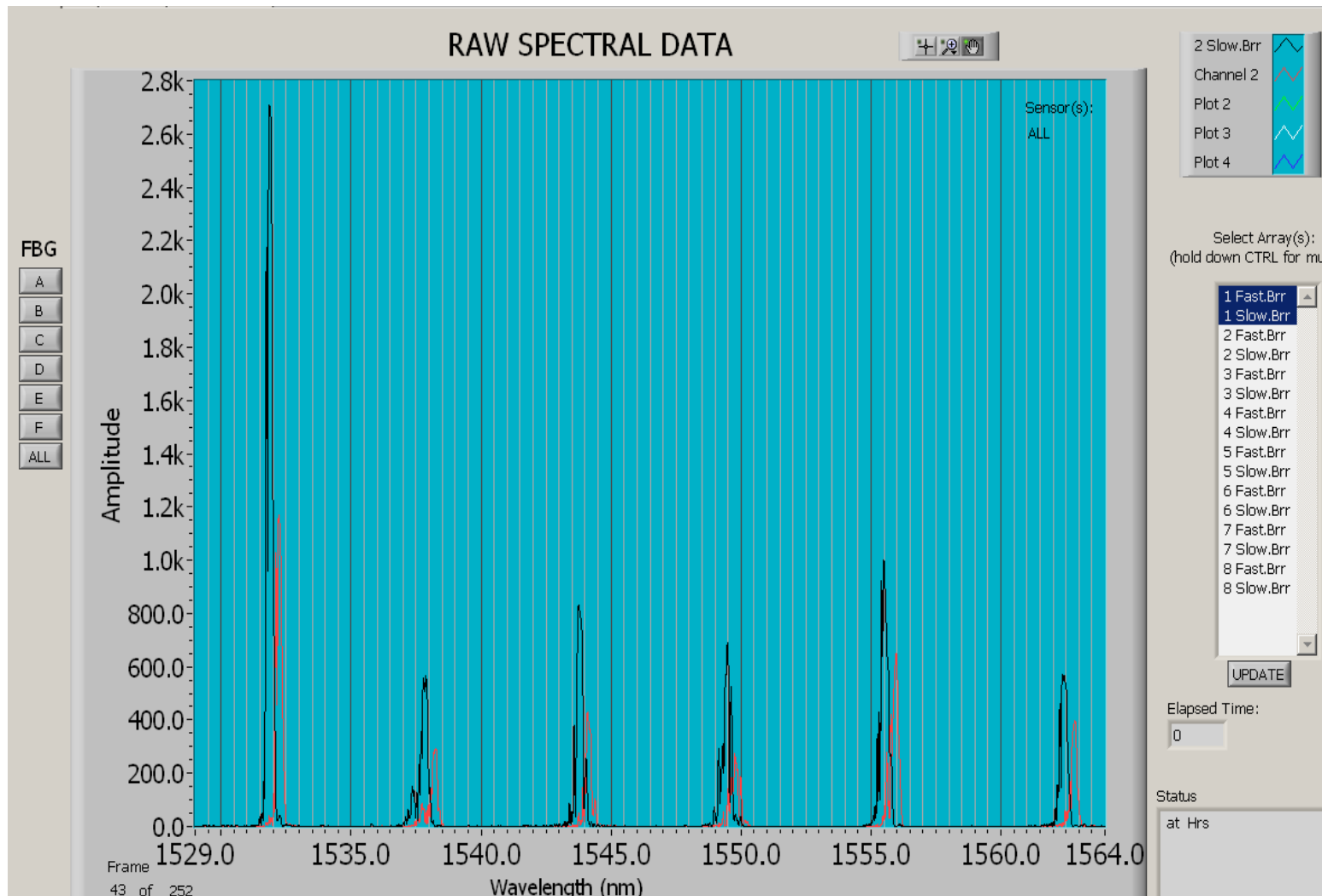
- Multi-axis fiber grating sensors may be used to perform “strain imaging” localizing and characterizing damage
- Optical signal processing has been improved to allow separation of in plane and out of plane “strain imaging” signals
- Evaluating & Applying new “strain imaging” algorithms

Experiment 2: Process Cure

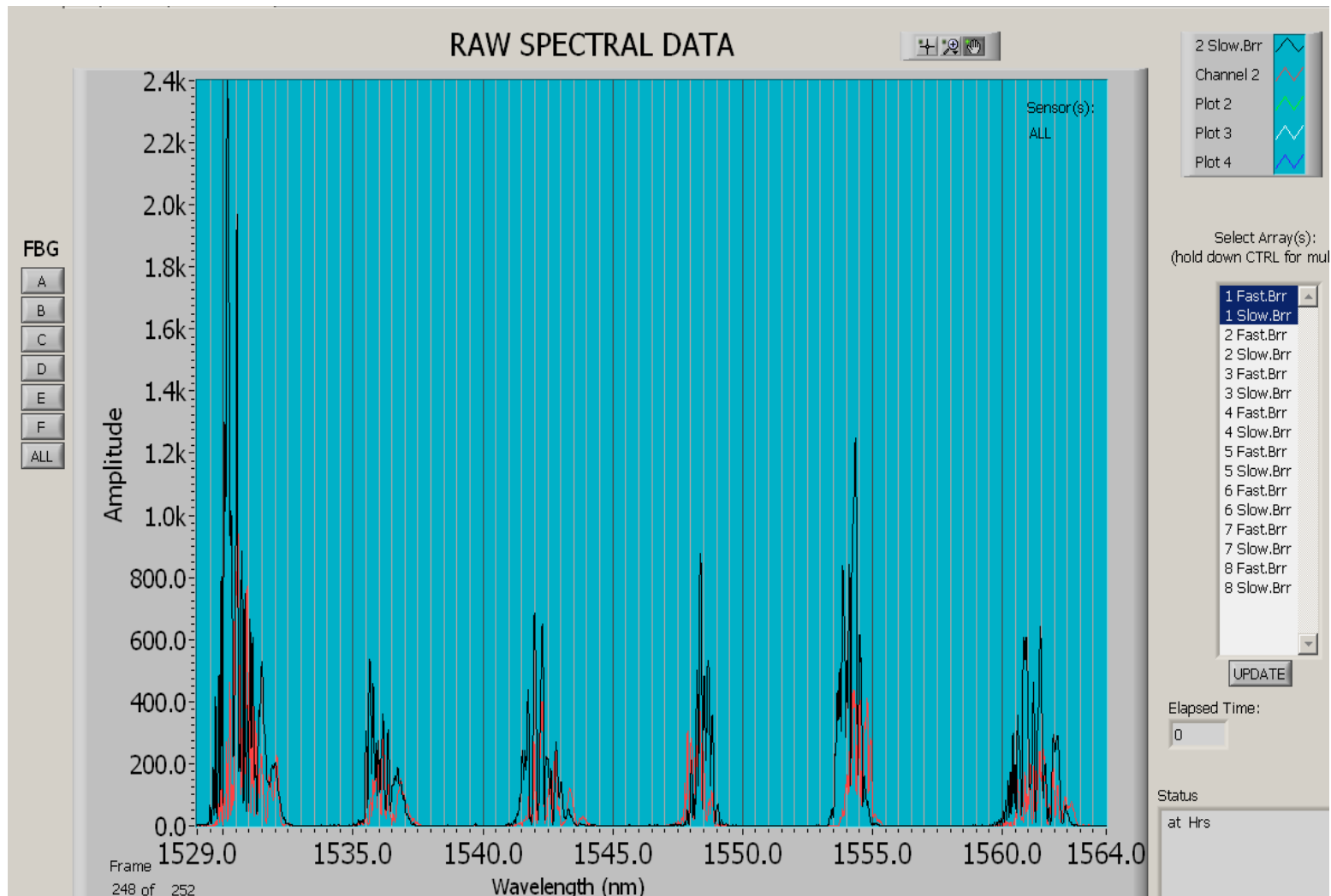
Watching Composites Cure



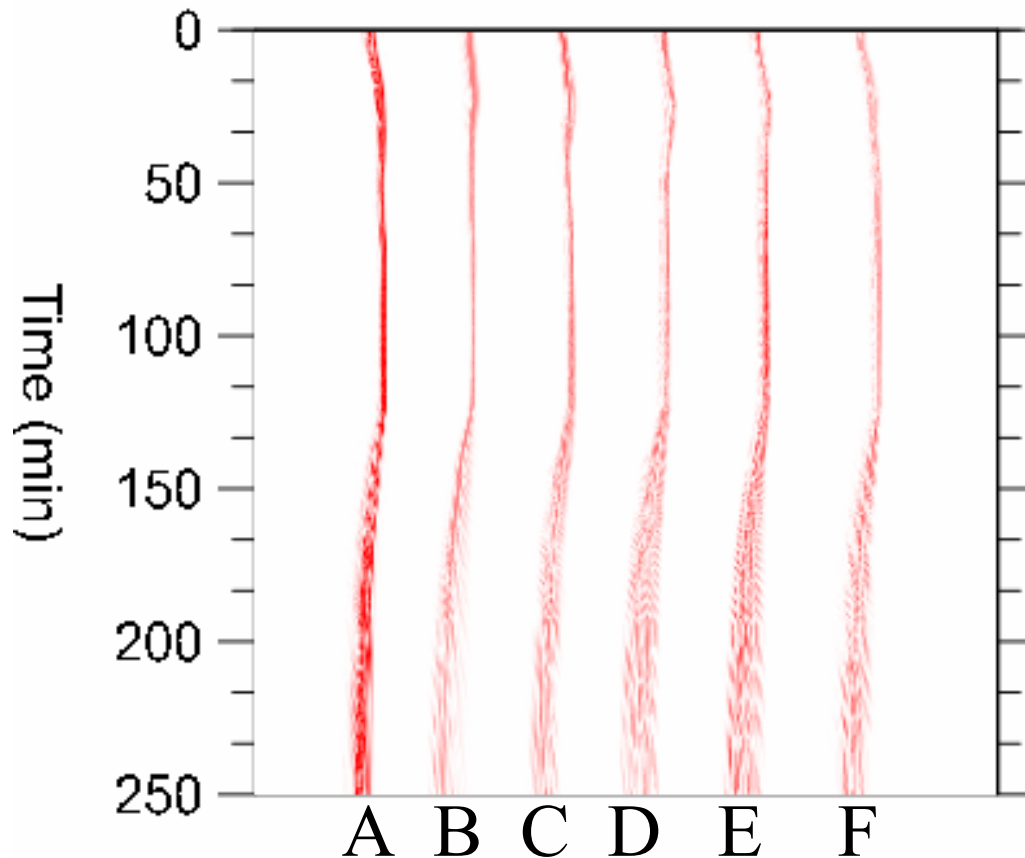
6 Sensors (Dual-Axis) as Cure Starts



6 Sensors (Dual-Axis) as Cure Finishes



Cure Cycle Information



Array 1, Axis 1

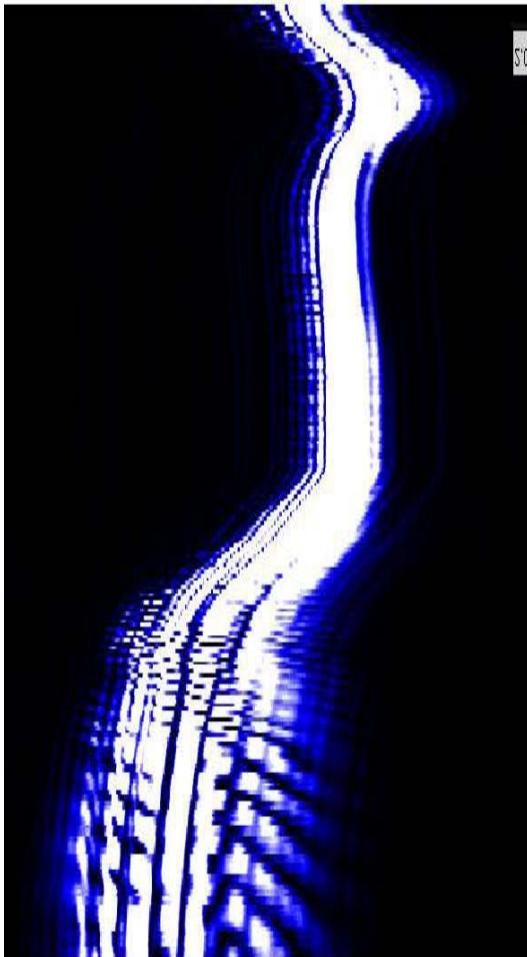
Spectral data:

6 FBG Peaks widen
as cross-linking occurs

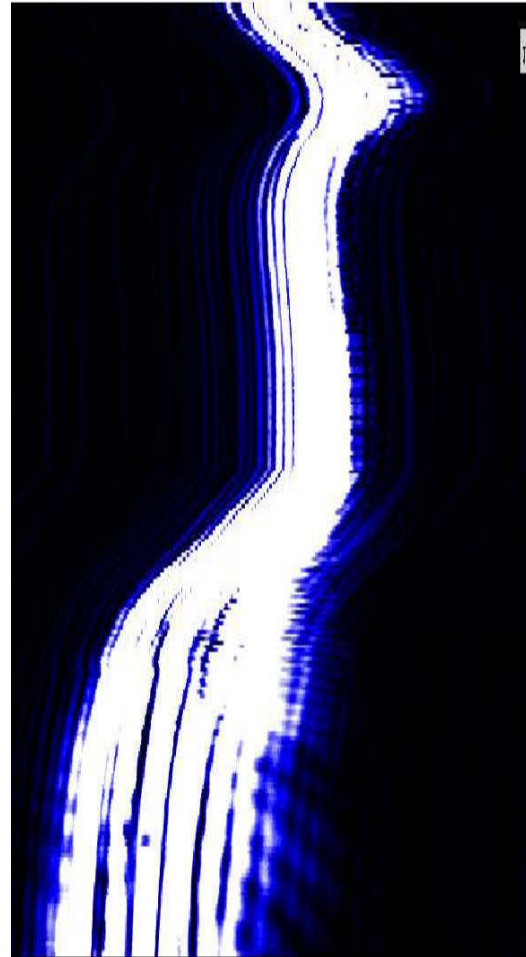
Array 1, Axis 1, Cure - EDW MC3

Reduced Data (Cross-Linking)

← cure time



1A: In-Plane



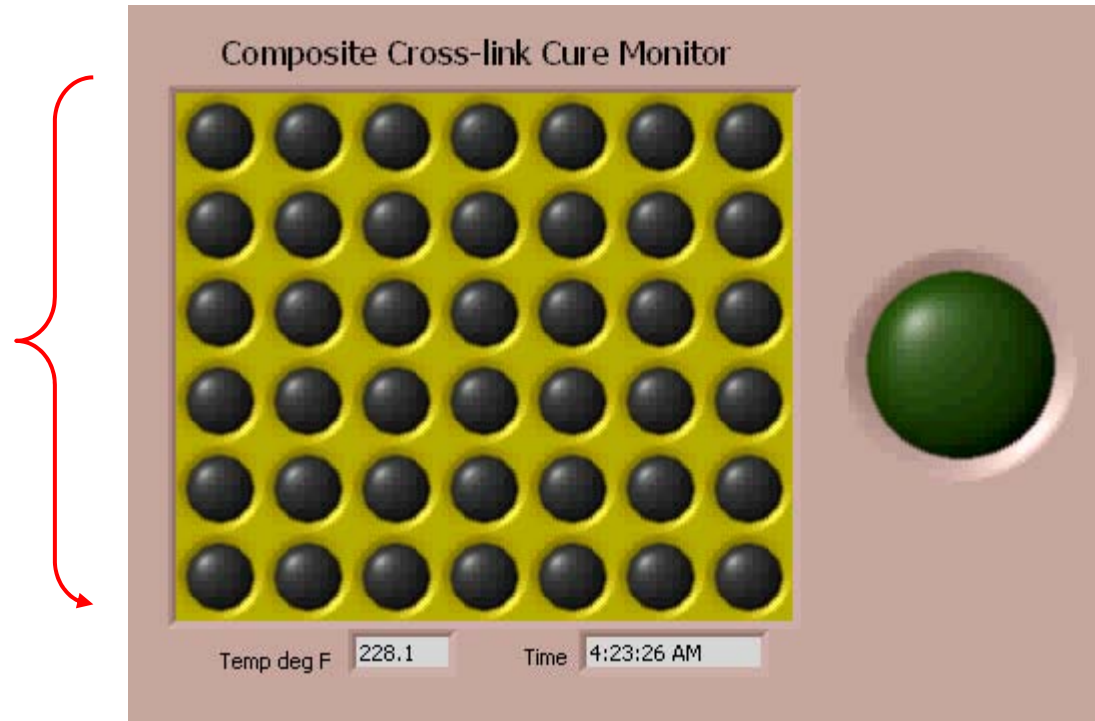
1A: Out-of-Plane

FBG 1A-
In-Plane/Out-of-Plane
Spectral data:

Close-up shows
FBG Peaks widen
as cross-linking occurs
during cure.

Cure & Process Verification Simulation

FBG Sensors/Discrete
Points inside Composite

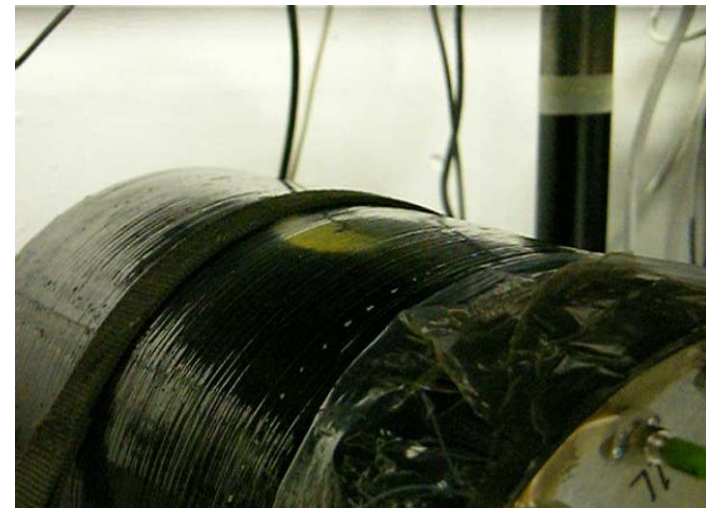
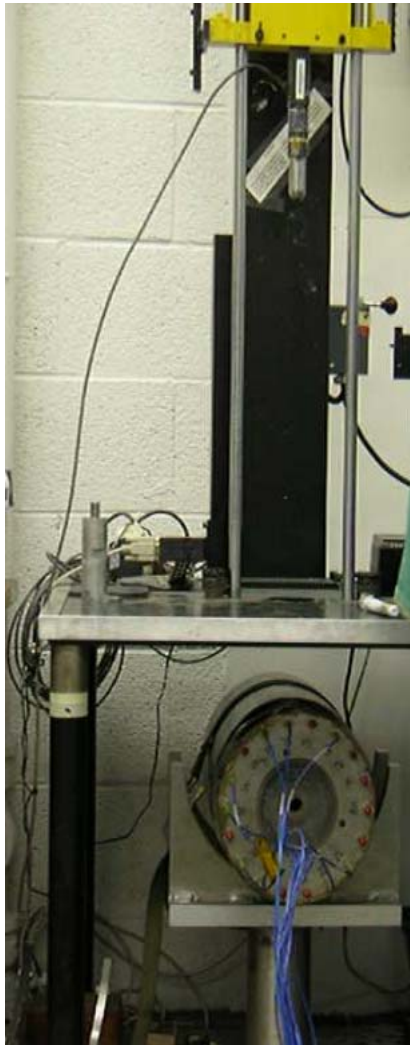


Manufactured Composite

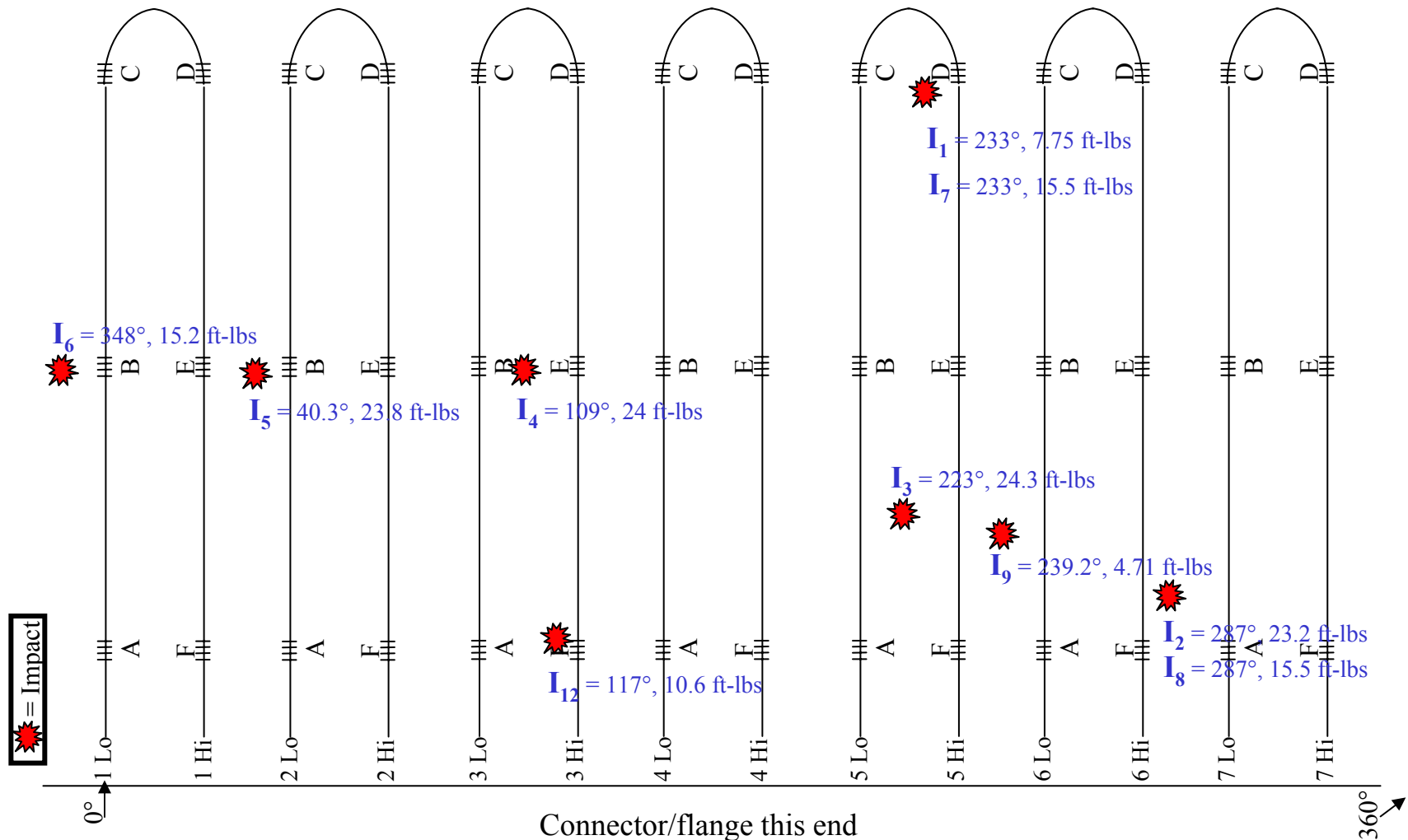


100% of 48 FBG sensors
Survived winding,
cure, casting, and handling

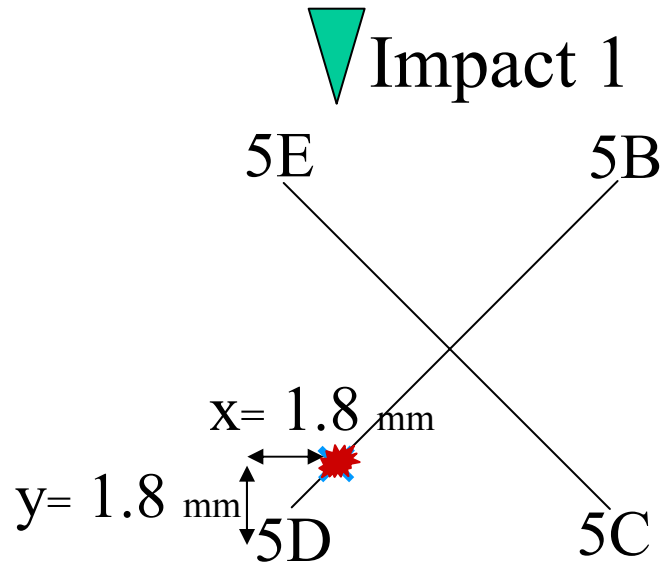
Experiment 3: Blind Impacts



Sensor & Impact Layout on Bottle



Impacts 1 & 2

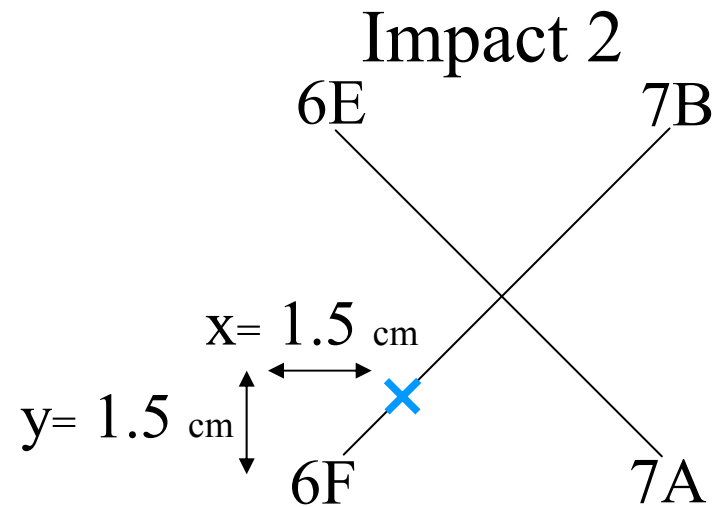


Force: 7.75 ft-lbs

Physical Measurement: 233.5°

26.8 cm Distance from Flange

49.3 cm from 0 Degrees



Force: 23.2 ft-lbs

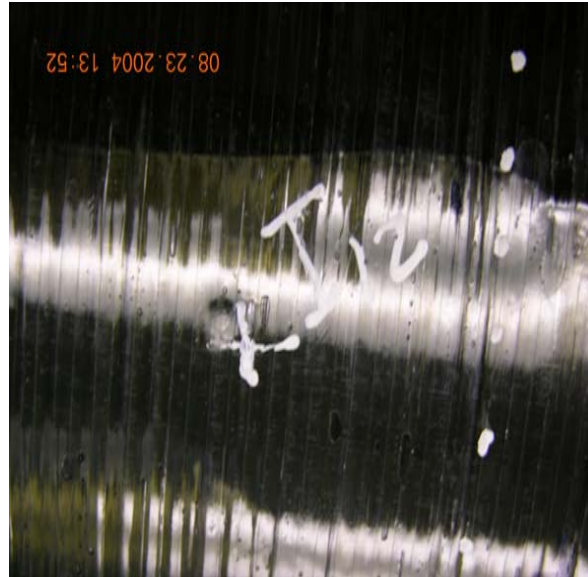
Physical Measurement: 286.58°

13 cm Distance from Flange

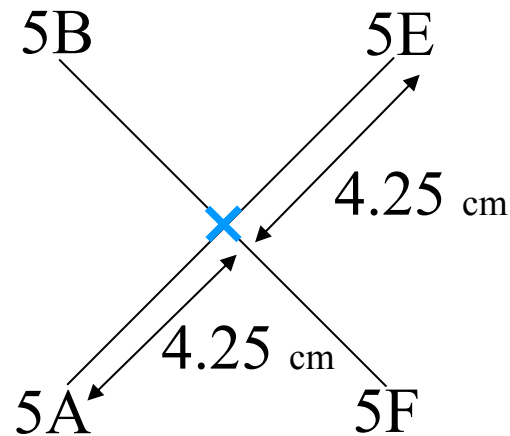
60.5 cm Distance from 0 Degrees

Impact Forces

Impact	Force (ft-lbs)
1	7.75
2	23.2
3	24.3
4	24
5	23.8
6	15.2
7	15.5
8	15.5
9	4.71
10	dome-15.76
11	dome-16.77
12	10.62



Impact 3



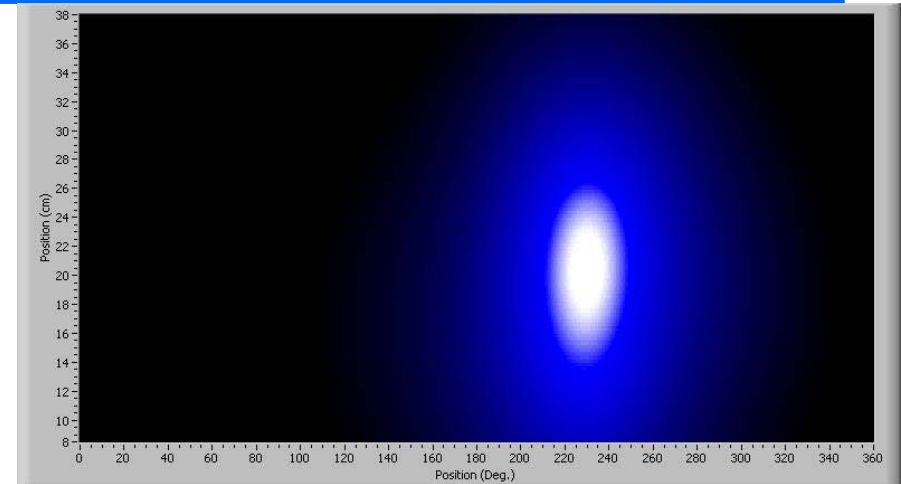
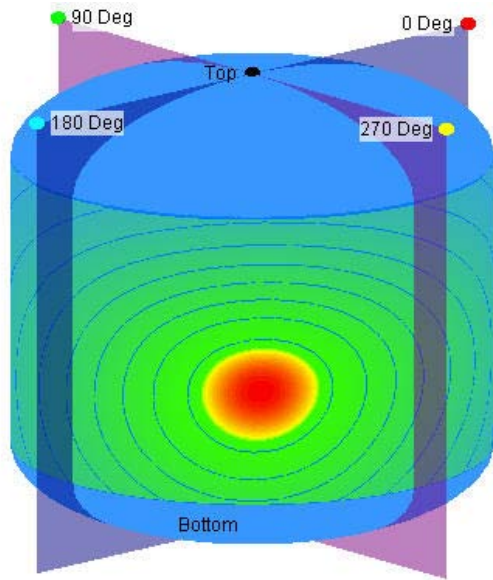
Force: 24.3 ft-lbs

Physical Measurement: 222.6 °

15.0 cm Distance from Flange

47 cm Distance from 0 Degrees

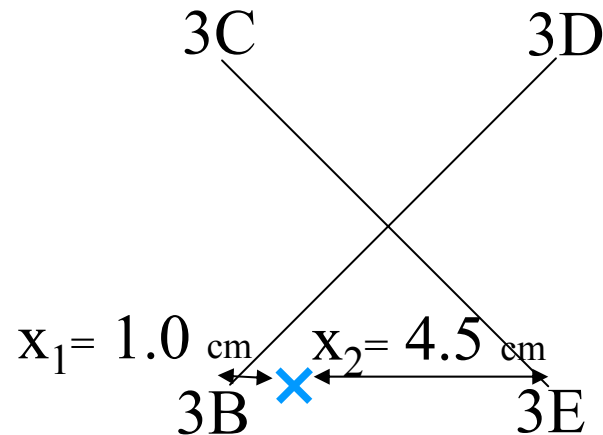
Impact 3



Force: 24.3 ft-lbs
15.0 cm Distance from Flange
47 cm Distance from 0 Degrees

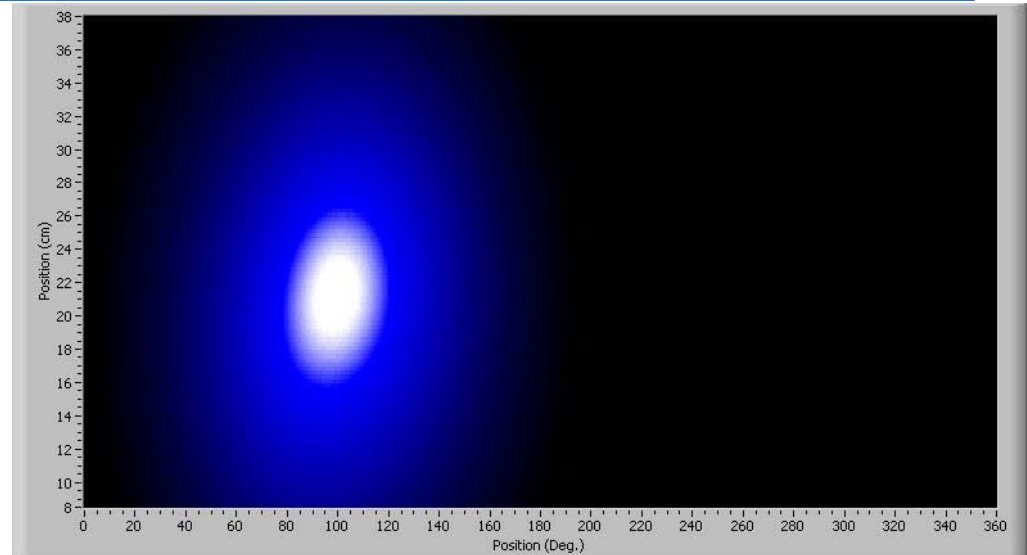
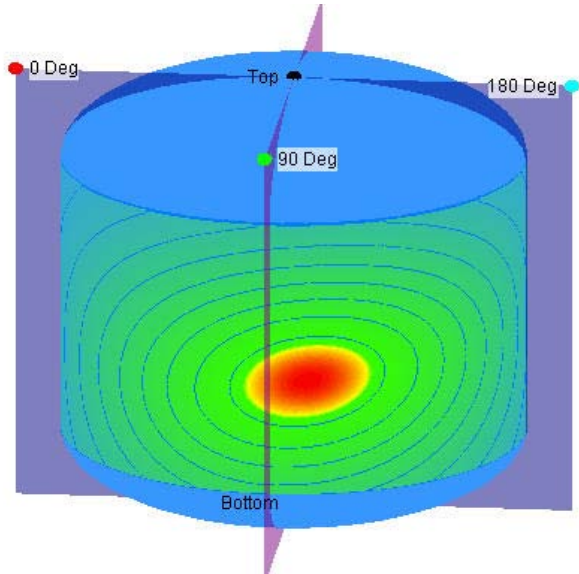
Physical Measurement: 222.6 °

Impact 4



Force: 24 ft-lbs: Physical
 Measurement: 108.9°
 18.2 cm Distance from Flange
 23 cm Distance from 0 Degrees

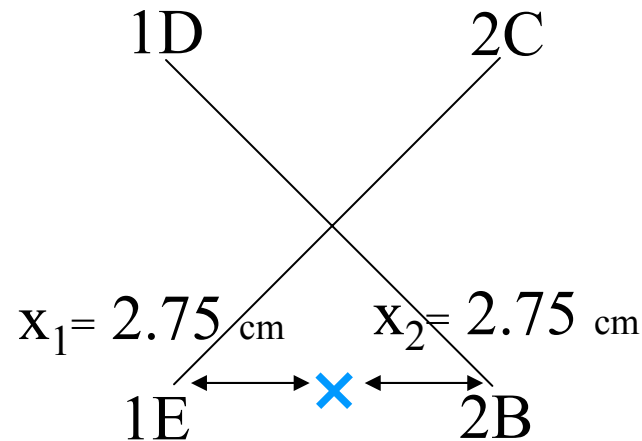
Impact 4



Force: 24 ft-lbs
18.2 cm Distance from Flange
23 cm Distance from 0 Degrees

Physical Measurement: 108.9 °

Impact 5



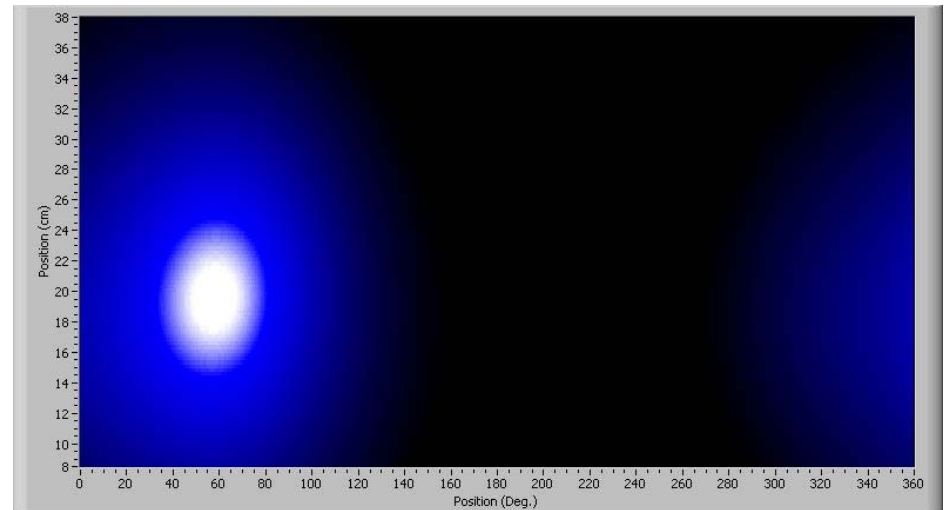
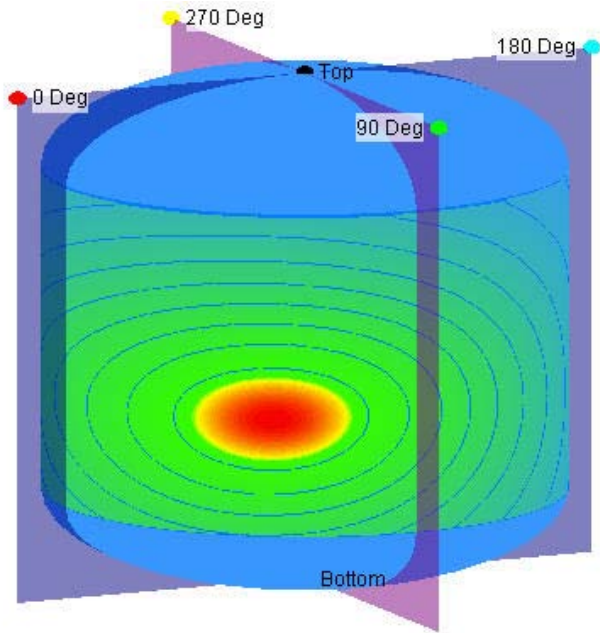
Force: 23.86 ft-lbs

Physical Measurement: 40.3°

18.0 cm Distance from Flange

8.5 cm Distance from 0 Degrees

Impact 5



Physical Measurement: 40.3°

Comparing Strain Imaging Results:

Ultrasonic Baseline

Before Impact

Edge of cylinder
(connector end)



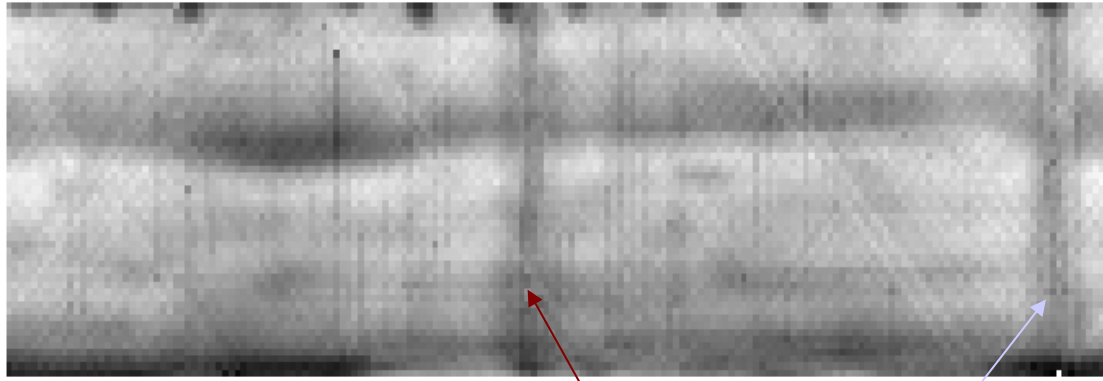
Edge of cylinder

0 deg

360 deg

Eddy Current Baseline (Before Impact)

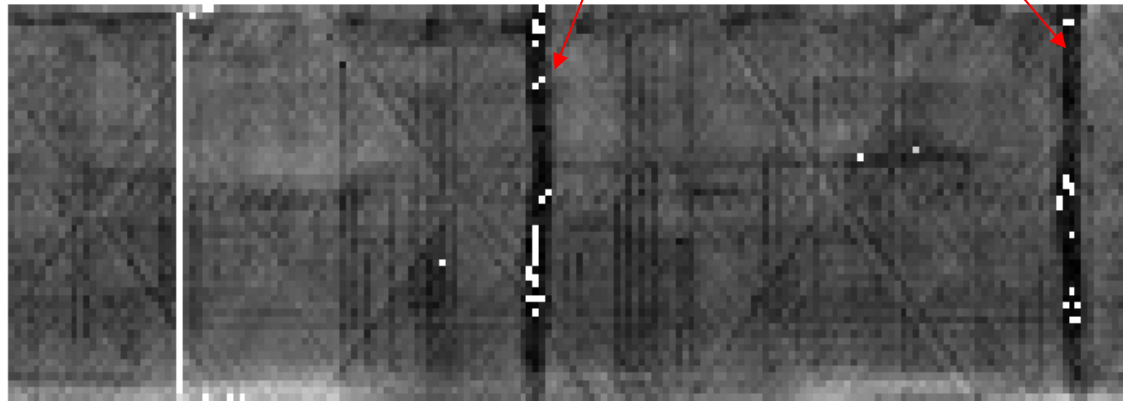
Blue Road Bottle Axial EC scan First Impact "alpha"



Edge of cylinder
(connector end)

Teflon tubing to dome sensor

Blue Road Bottle Axial EC scan Before Impact "Tau" 8-11-04



Edge of cylinder

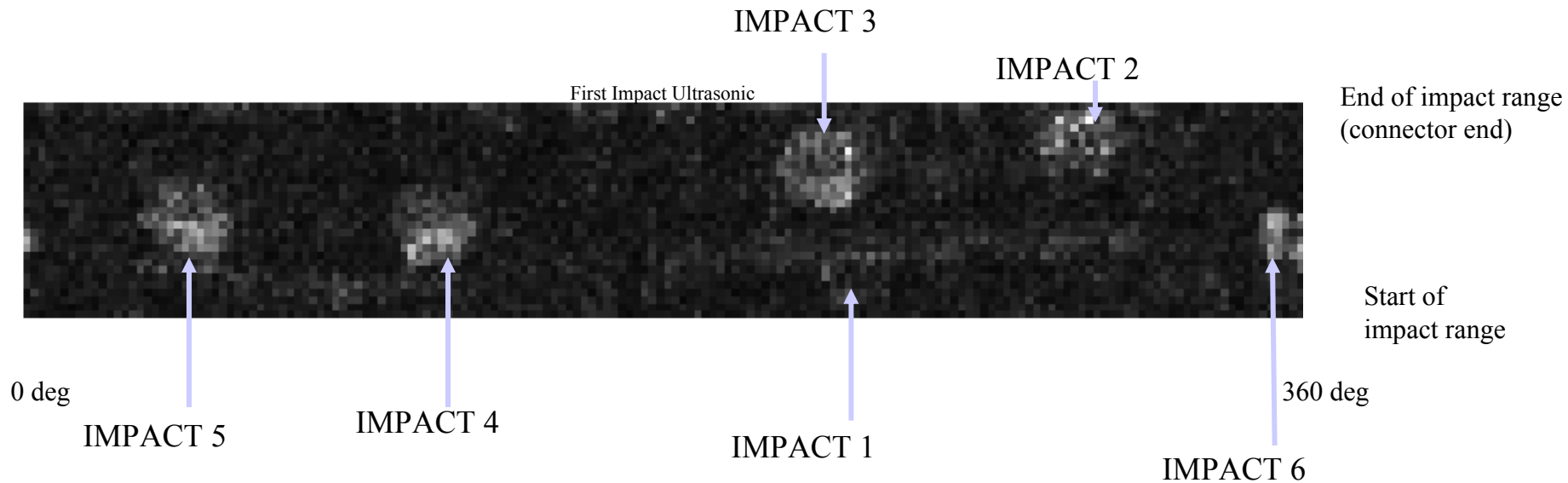
Edge of cylinder
(connector end)

0 deg

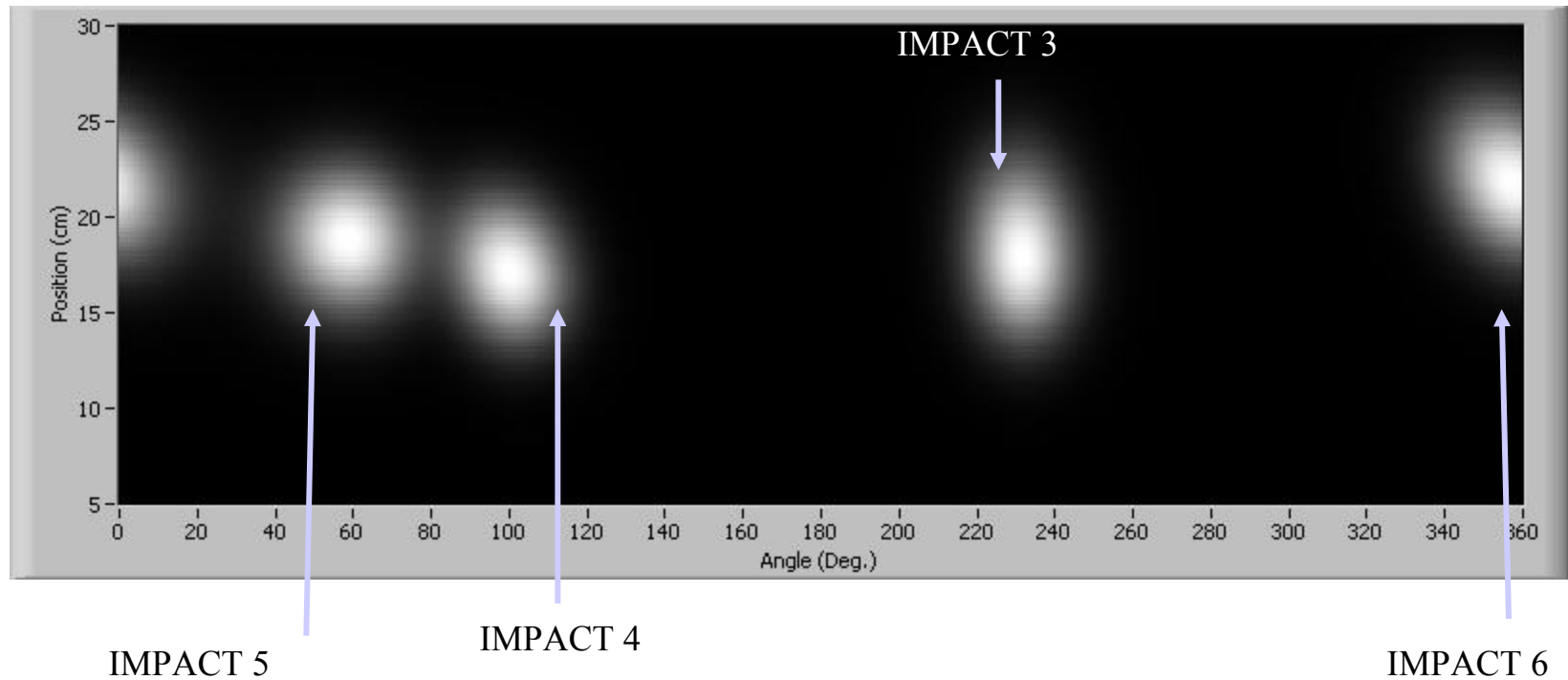
360 deg

Edge of cylinder

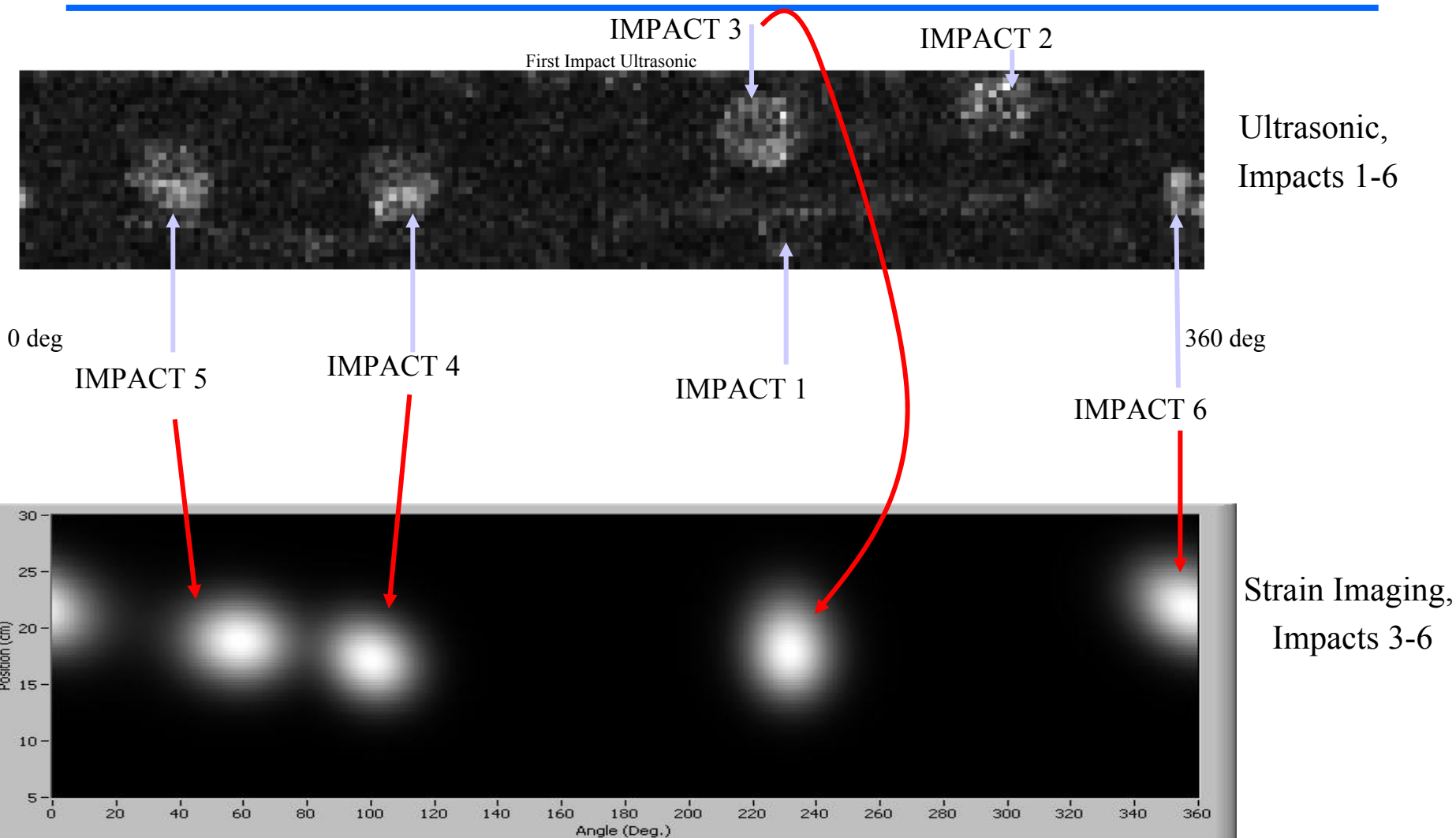
Ultrasonic, Impacts 1-6



Strain Imaging, Impacts 3-6

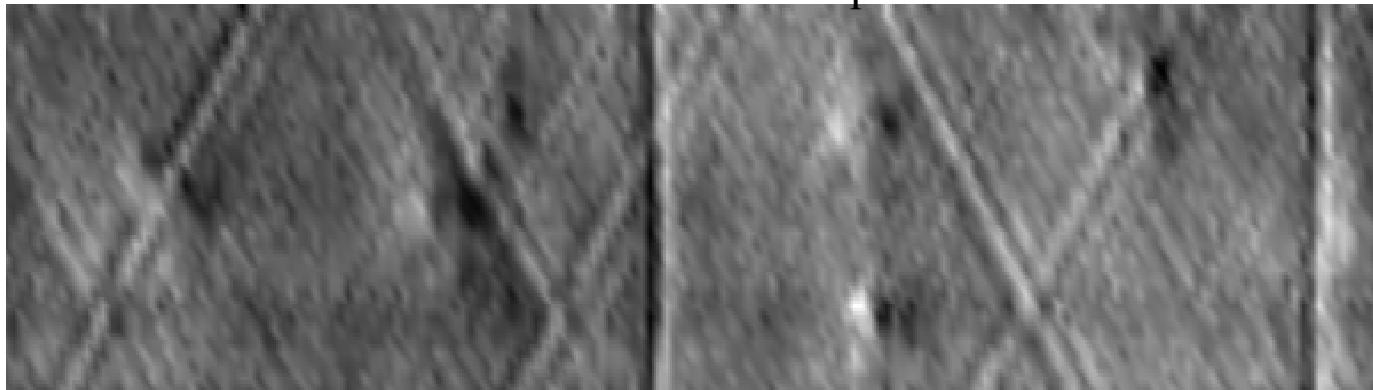


Comparison of NDE Scans



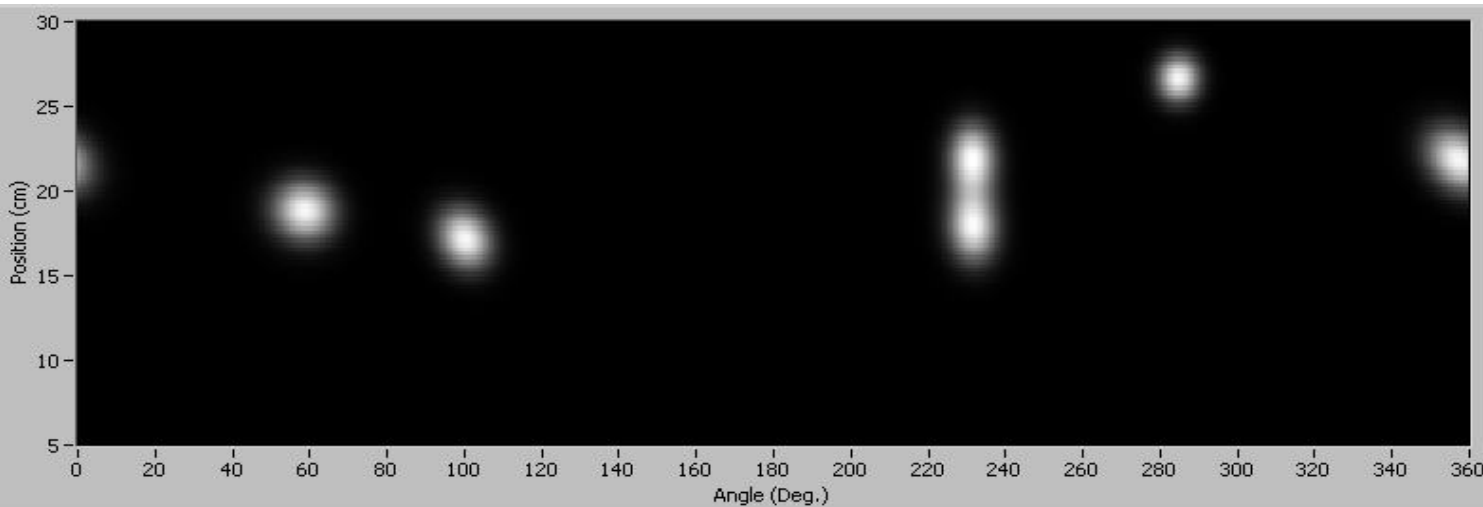
Pulse Eddy Current, Impacts 1-9, 12

PEC after second Impact



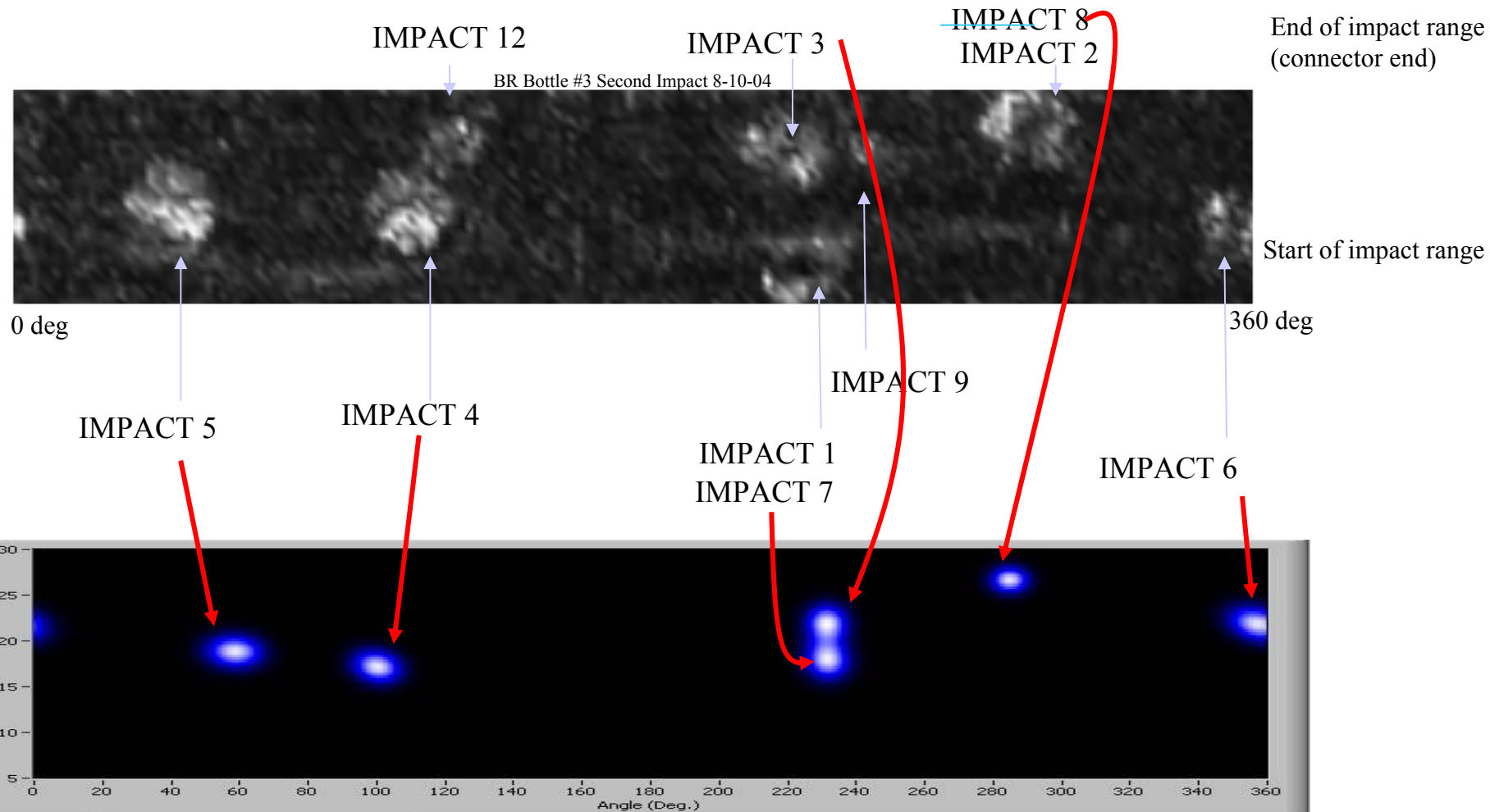
Pulse Eddy Current,
Impacts 1-9, 12

0 deg 360 deg

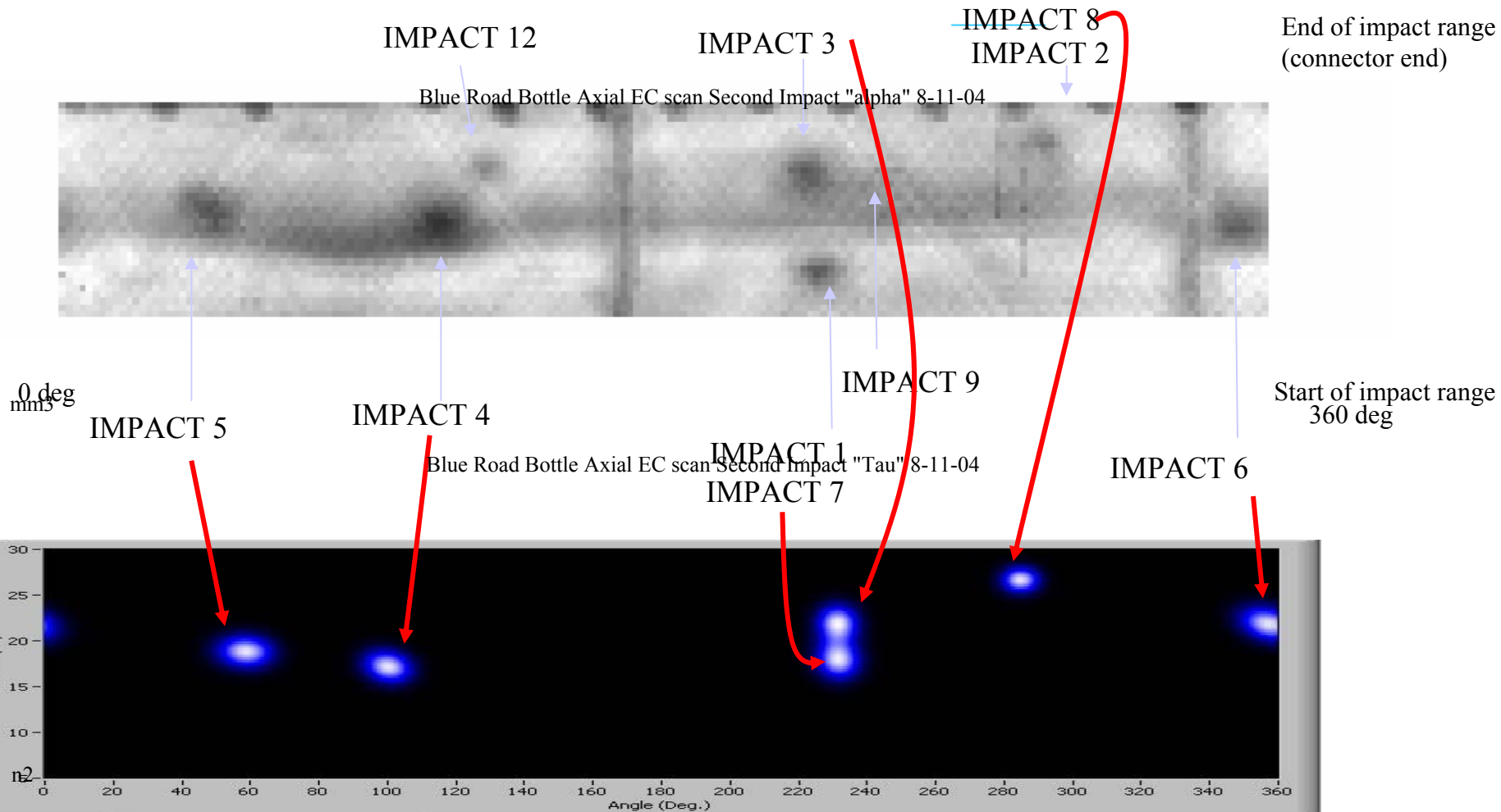


Strain Imaging,
Impacts 3-8

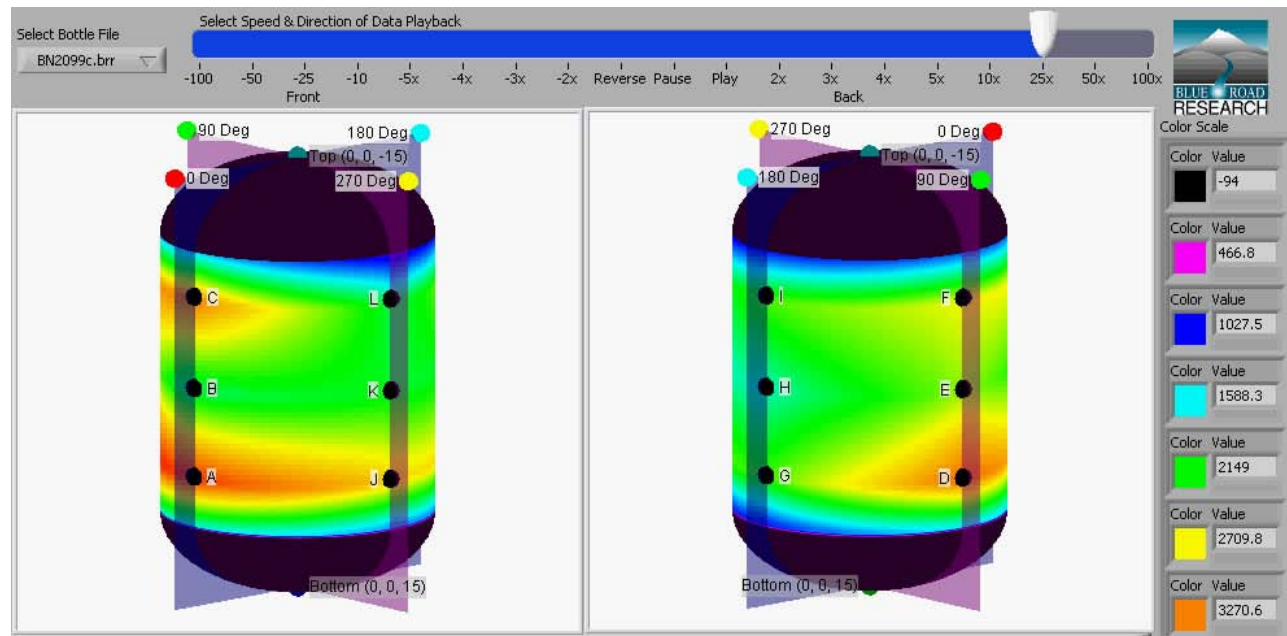
Ultrasonic: Impacts 1-9, 12 & Strain Imaging: Impacts 3-8



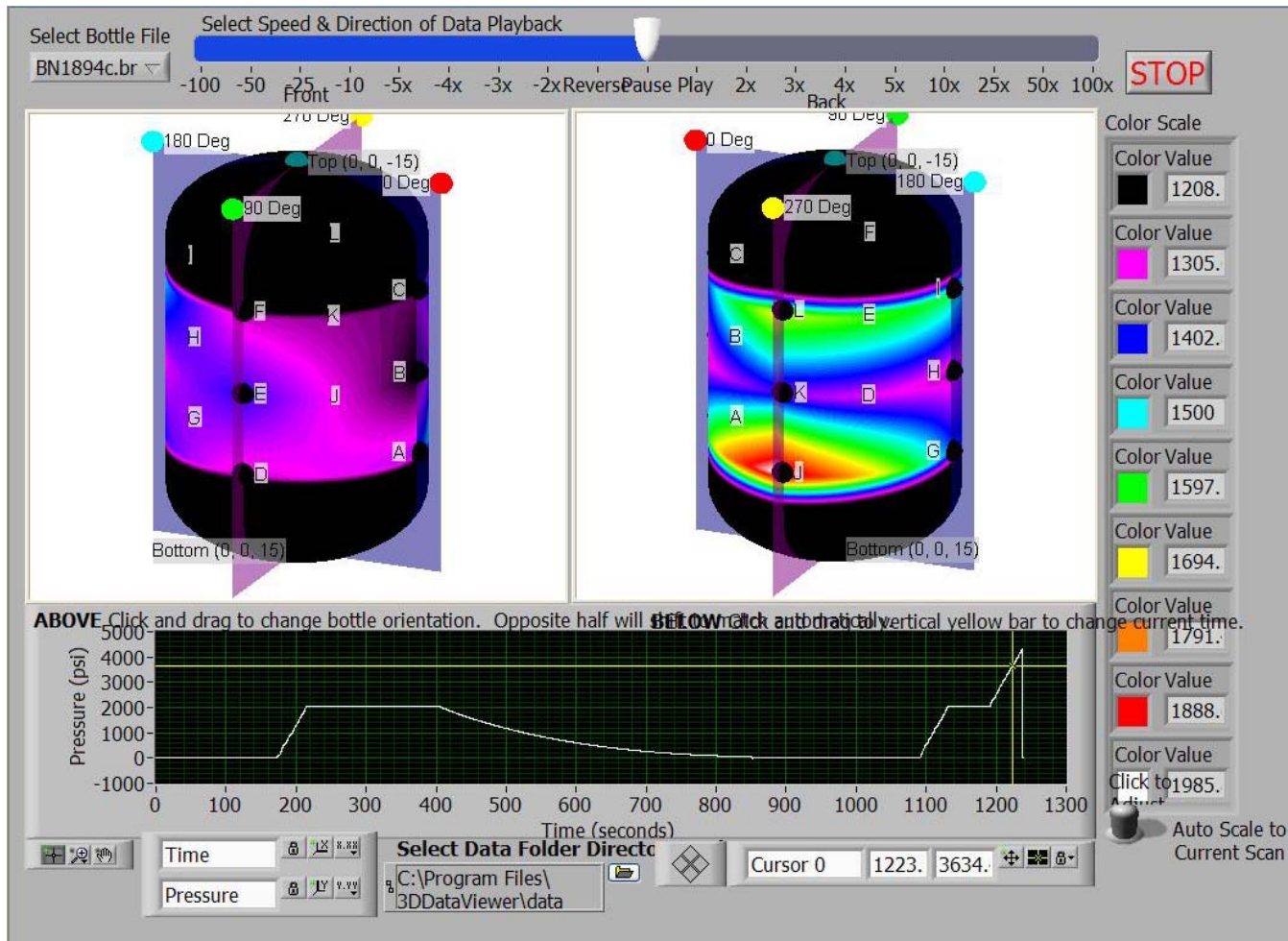
FBG overlaid – Eddy Current: Impacts 1-9, 12 & Strain Imaging: Impacts 3-8



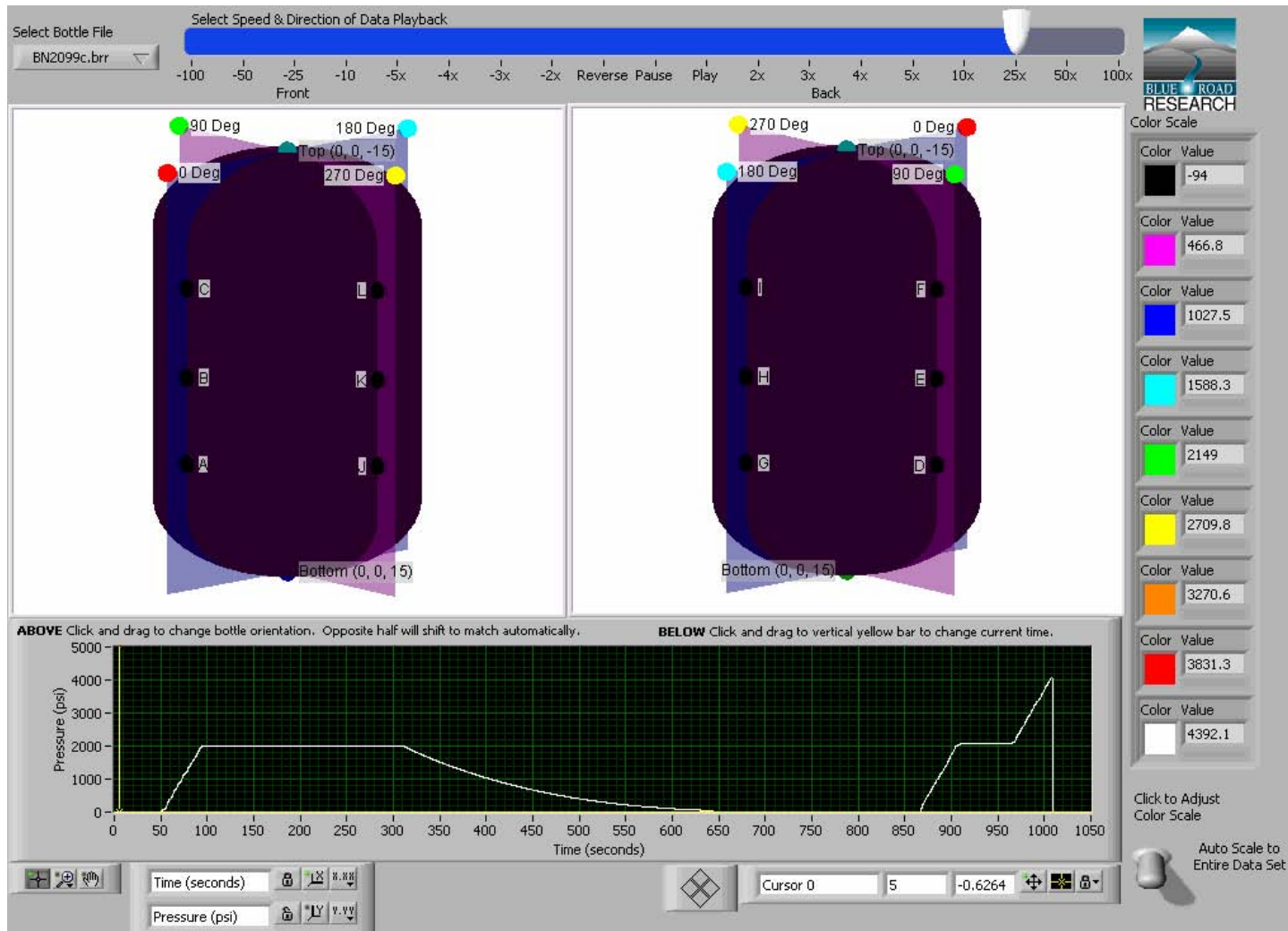
Dynamic Strain 'Imaging'



Dynamic Strain Imaging Interface



Dynamic Strain Imaging Concept



Conclusions

Strain Imaging offers the following:

- complementary to ultrasonic & eddy current NDE methods
- ‘On-demand’ monitoring capabilities
- Rapid ($<1/10^{\text{th}}$ the time of UT & EC) scanning
- Ability to catalog/compare composite health history over time
- Real-time feedback during manufacturing (process cure + FEA model verification)
- Ability to differentiate transverse and axial damage to 10 microstrain & 3 microstrain, respectively
- Locate damage in 8 out of 9 impacts to usually no greater than 2 cm

Future Work

- >20-40 Hz - kHz dynamic strain
- Wizard interface, allowing dynamic configuration of any composite geometry
- Label damage by type
- Calibrated output values
- Data viewable by multiple formats in real-time (includes raw spectral format, strain values, FEA export, etc.)
- Manufacturing Process Cure/FEA Verification
- Continue to build database of damage signatures
- Hardware improvements in speed, size, & resolution